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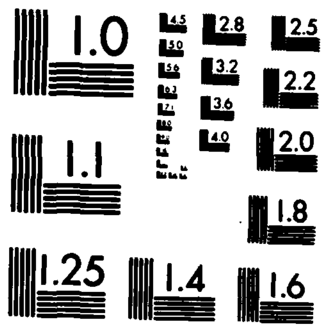

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

OPTIMIZATION OF GUIDANCE AND CONTROL USING
FUNCTION MINIMIZATION AND NAVSTAR/GPS

by

Vicente Chavez Garcia, Jr.

September 1984

Thesis Advisor: George J. Thaler

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Optimization of Guidance and Control using Function Minimization and NAVSTAR/GPS

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ABSTRACT

A carefully designed controller, tuned to minimize a performance criterion based on representation of the added drag due to steering, can minimize propulsion losses. A computer simulation modeling the Sea-Land Mclean (SL-7) containership was coupled to a function minimization subroutine and a sea-state generator subroutine to accomplish the tuning. Storing these optimal controller parameters in a look up table as functions of ship state, sea state, and encounter angle, this technique can be used as an adaptive controller. Satellite platforms can give continuous environmental operating conditions which may be used to select proper controller parameters to provide continuous operation on a minimum of the cost function. The SL-7 containership computer model was tested in calm waters and in a seaway.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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I. INTRODUCTION

An overall rise in fuel prices has led to an increasing interest in the design of autopilots for ships. The purpose of the automatic steering control is to minimize the propulsion losses, which are caused by added drag due to steering of the ship. Minimizing a performance criterion based on added drag due to steering can reduce fuel consumption. Claims by many researchers indicate that a carefully designed controller could save from one to two percent of fuel. For large containerships this could amount to more than $100,000.00 per year savings.

To study the optimization problem, models of both the ship and its operating environment are required. What type of computer model should be used to represent the ship? Chapter two addresses the development of several models. Since the best model was desired it was decided to use the equations of motion to simulate the ship in our Fortran program. The basic Nomoto models give an adequate description of ship steering dynamics for design. The Nomoto second- and third-order models were developed from the equations of motion as defined by a series expansion including all terms (both linear and nonlinear) for which hydrodynamic coefficients were available. An interactive program that utilized the Nomoto models to model the ship was also used. Two independent programs were developed to aid in the design of the controller.

What is an adequate cost function which represents the added drag due to steering? Chapter three addresses the classical cost function used by many researchers.

Since a variety of control algorithms are possible one must ask if one algorithm provides a lower minimal cost than

another. Chapters four, five and six address the selection of the controller which provides the minimum value of added drag due to steering.

Ship dynamics change with operating conditions such as ship speed , sea state , and encounter angle. Therefore an adaptive controller must be used to provide minimum added drag due to steering. Chapter seven development of an approach to an adaptive controller utilizing satellite information.

Conclusions were drawn from these experiments and are presented in Chapter eight. This thesis investigated only course keeping with emphasis on minimizing rudder and yawing activity to reduce fuel consumption. Presented in this Chapter are recommendations for future study where the objective is track following which would be important for ships required to follow stringent routes. It is also important for other systems such as satellites, missiles, aircraft, where the controller minimizes yaw error to keep the system on track.

II. COMPUTER MODELS

The model which best represents ship-steering dynamics is a Taylor's series expansion of the force and moment relationships around a selected steady-state operating point. The resulting equations are commonly known as the equations of motion [Ref. 1]. A computer program was developed using known available data on the hydrodynamic coefficients for the SL-7 containership to provide a computer simulation of the ship. The computer program is shown in Appendix A. Figure 2.1 shows the block diagram. Small yaw command angles are used, for example YAWC= 1.0 / 57.296 represents a yaw command change of one degree.

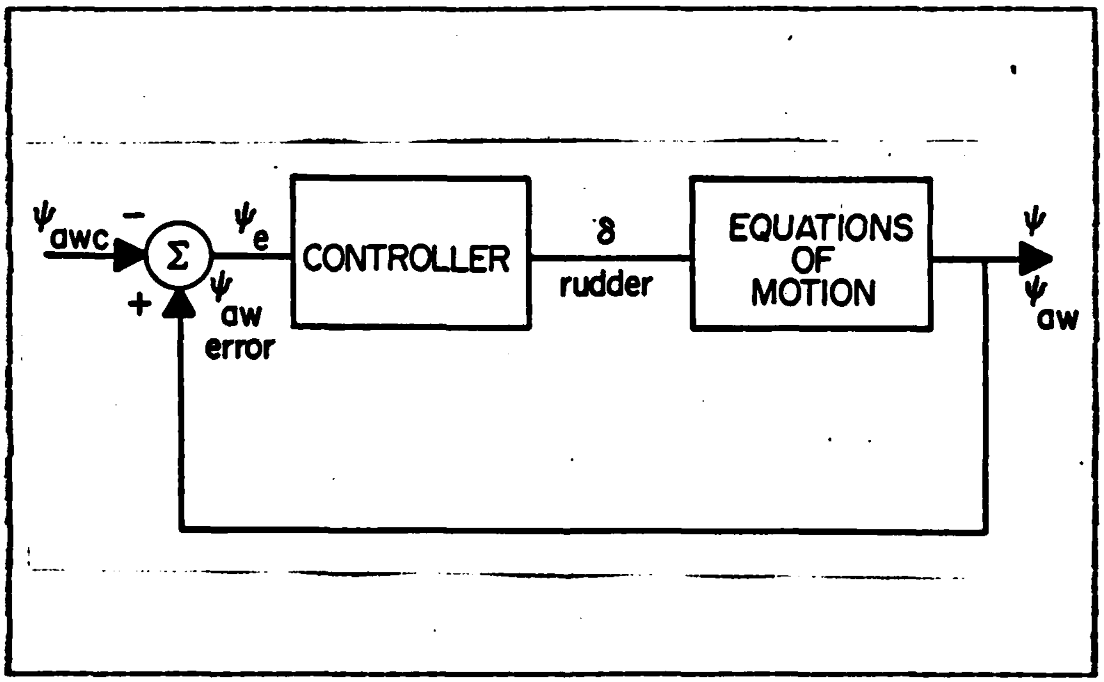

Figure 2.1 BLOCK DIAGRAM

To obtain the Nomoto second- and third-order transfer functions from the equations of motion, the function minimization subroutine was used to obtain the coefficients. Figure 2.2 shows the scheme used to obtain the Nomoto transfer functions. The computer program is shown in Appendix A.

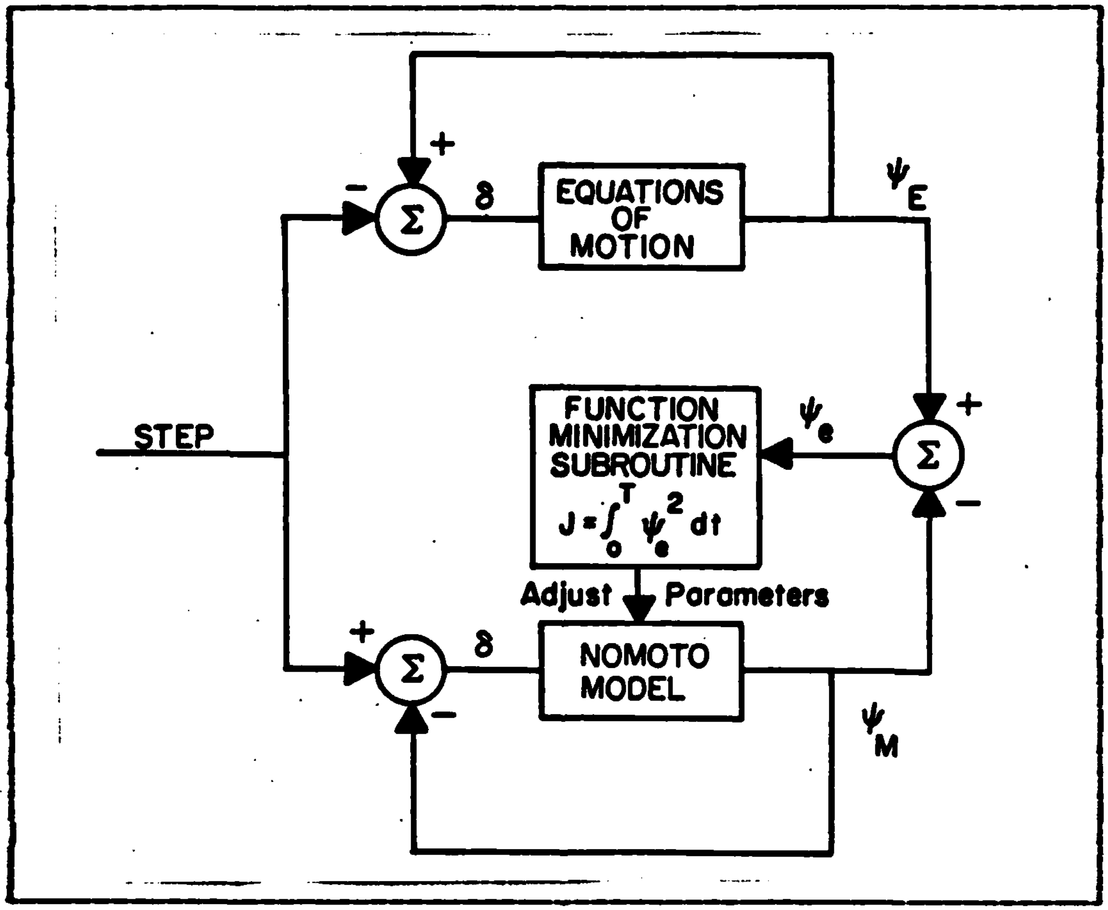

Figure 2.2 DETERMINATION OF NOMOTO MODELS

The Nomoto models were checked against analytic results from linearized equations.

Proceeding to the second-order Nomoto equation:

$$\psi(S)/\delta(S) = K/S*(1+T*S) \tag{2.1}$$

Deriving the second-order Nomoto transfer function from the yaw equation only, the result is

$$\psi(S)/\delta(S) = 0.040893/S*(1+8.539932*S)$$

and using function minimization as in Figure 2.2

$$\psi(S)/\delta(S) = 0.0409221/S*(1+8.5520782*S)$$

and the agreement is obvious. Using function minimization with both yaw and sway equations with linear terms only, the results are:

$$\psi(S)/\delta(S) = 0.1072741/S*(1+31.9199524*S)$$

If the nonlinear terms are included but the perturbation is small

$$\psi(S)/\delta(S) = 0.1072082/S*(1+31.8907013*S)$$

and it is clear that the nonlinear terms contribute little.

Proceeding to the third-order Nomoto equation:

$$\psi(S)/\delta(S) = K*(1+TZ*S)/S*(1+TP1*S)*(1+TP2*S) \tag{2.2}$$

The parameters were calculated and checked by using function minimization as in Figure 2.2. The results are given in Table 1. It is clear that the answers obtained by function minimization agree closely with the analytic solutions.

TABLE 1

THIRD-ORDER NOMOTO MODEL FOR THE SL-7

speed	K		TZ		TP1		TP2	
knots	calc	comp	calc	comp	calc	comp	calc	comp
16	.0738	.0738	22.57	22.95	12.946	12.946	107.583	107.583
23	.1067	.1061	15.67	15.70	9.014	9.006	75.130	74.846
32	.1477	.1477	11.28	11.28	6.470	6.467	53.793	53.793

Analytical equations used to calculate second-order Nomoto transfer function coefficients are:

$$K = N_{\delta} / N_{r} \quad ; \quad T = -(I_{z} - N_{\dot{r}})/N_{r}$$

Analytical equations used to calculate third-order transfer function coefficients are:

$$K = (N_{\delta} - N_{v} * Y_{\delta} / Y_{v}) / (N_{r} - N_{v} * (Y_{r} - M*U) / Y_{v})$$
$$TZ = -((M - Y_{\dot{v}}) * N_{\delta} - N_{\dot{v}} * Y_{\delta}) / (Y_{v} * N_{\delta} - N_{v} * Y_{\delta})$$
$$TP1*TP2 = -((M - Y_{\dot{v}}) * (I_{z} - N_{\dot{r}}) - N_{\dot{v}} * Y_{\dot{r}}) / (N_{v} * (Y_{r} - M*U) - Y_{v} * N_{r})$$
$$TP1+TP2 = ((M - Y_{\dot{v}}) * N_{r} + (I_{z} - N_{\dot{r}}) * Y_{v} + N_{\dot{v}} * (Y_{r} - M*U) + Y_{\dot{r}} * N_{v}) / (N_{v} * (Y_{r} - M*U) - Y_{v} * N_{r})$$

The nondimensionalized hydrodynamic coefficients for the SL-7 containership are shown in Table 2.

TABLE 2

HYDRODYNAMIC COEFFICIENTS FOR THE SL-7

axial force		lateral force		moment z-axis	
$X'_{\dot{u}}$	= -0.0001	Y'_{v}	= -0.00758	N'_{v}	= -0.00213
X'_{uu}	= -0.0003	Y'_{r}	= 0.0023	N'_{r}	= -0.00105
X'_{vr}	= 0.0039	Y'_{δ}	= 0.00145	N'_{δ}	= -0.0007
X'_{vv}	= -0.0012	Y'_{vvr}	= 0.01	N'_{vvr}	= -0.015
$X'_{\delta\delta}$	= -0.0005	Y'_{vrr}	= -0.008	N'_{vrr}	= -0.008
		Y'_{vvv}	= -0.03	N'_{vvv}	= 0.01
		Y'_{rrr}	= 0.003	N'_{rrr}	= -0.006
		$Y'_{\delta\delta\delta}$	= -0.0005	$N'_{\delta\delta\delta}$	= 0.0001

III. COST FUNCTION

In recent years, many have studied the problem of [Ref. 2] [Ref. 3] [Ref. 4] [Ref. 5] [Ref. 6] [Ref. 7] [Ref. 8] [Ref. 9] [Ref. 10] [Ref. 11] [Ref. 12] [Ref. 13] [Ref. 14] optimizing an automatic ship-steering controller for minimum fuel consumption. It is well known that additional drag is introduced by steering and that both the rudder motion and the yawing motion contribute to this added drag. A measure of the added drag given as a cost function is

$$J = 1/T\int_{0}^{T} (\lambda * \psi_{\epsilon}{}^{2} + \delta^{2}) \, dt \qquad (3.1)$$

where ψ_{ϵ} = yaw error

δ = rudder angle

λ = weighting factor

While this expression is an approximation, it is convenient for shipboard use because ψ_{ϵ} and δ are readily measurable. There is no general agreement on numerical values for the weighting factor, λ , and in this study the values used were chosed from the work of *R.E. Reid [Ref. 7] for the* SL-7.

The weighting factors for the operating range of the ship are shown in Table 3.

TABLE 3

WEIGHTING FACTOR

ship speed (knots)	weighting factor
16	16.796
23	8.128
32	4.2

Reid's work shows the relationship of weighting factor to the closed-loop natural frequency, mass, pivot point, ship speed, X''_{vr} and $X'_{\delta\delta}$ hydrodynamic coefficients. It is shown in Equation 3.2. Reid chose a closed-loop natural frequency of 0.05 rad/sec which experimentally showed at this frequency, the weighting factor in the cost function, provided good representation of the added drag due to steering.

$$\lambda = 2*M*(1+X''_{vr})*(CP/L)*\omega^2 /(\rho/2)*(1+X_{\delta\delta} *U^2) \qquad (3.2)$$

IV. CONTROLLER DESIGN USING ICSOS

The Interactive Control System Optimization and Simulation (ICSOS) package finds optimum values for unknown (free) parameters in a control system design problem and/or performs simulation of the system. An example of usage of ICSOS is shown in Appendix B.

In preliminary studies ICSOS was used with Nomoto models to study controller characteristics in calm water. The function minimization subroutine adjusted the controller parameters to minimize the cost function. Figure 4.1 shows the scheme used to evaluate the controller parameters.

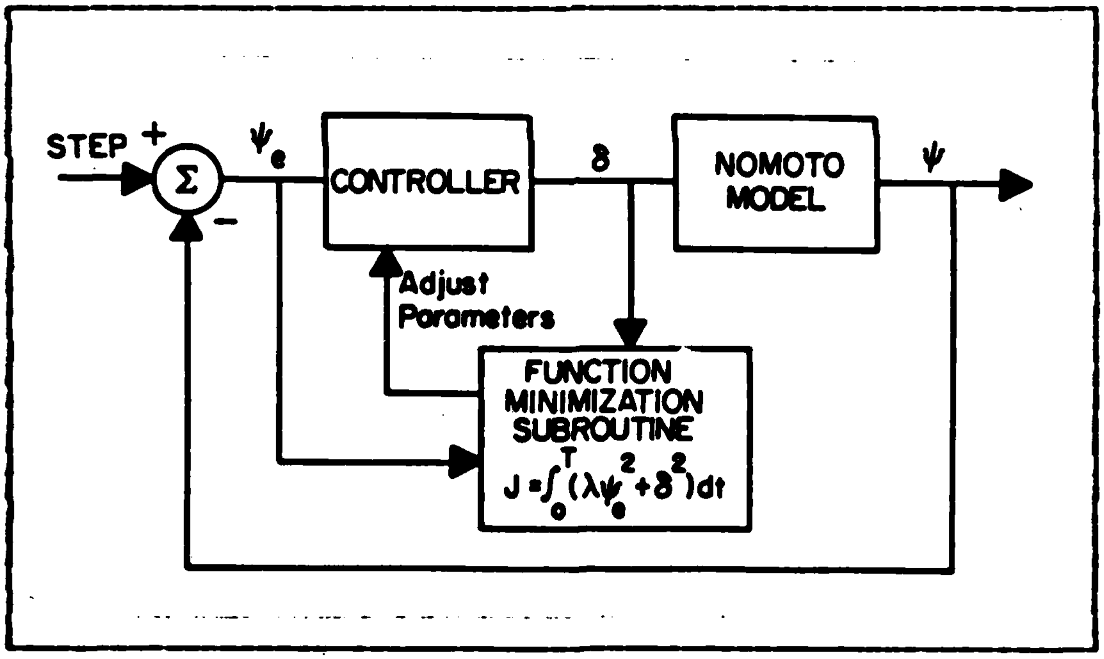

Figure 4.1 OPTIMIZATION OF CONTROLLER

Reid [Ref. 7] uses the second-order Nomoto model of equation 2.1 for the SL-7 and also uses a controller described by

$$Gc(S) = K1*(1+T1*S) / (1+T2*S) \qquad (4.1)$$

His results are given in Table 4.

TABLE 4

REID'S RESULTS

speed knots	plant K	plant T	weighting factor	controller gains K1	T1	T2
16	0.1084	90.36	16.796	0.4556	89.51	10.06
23	0.1556	64.67	8.128	0.3769	62.60	8.308
32	0.2167	45.45	4.2	0.3188	44.92	7.066

Using this plant and weighting factor values but applying ICSOS, results were obtained and shown on Table 5.

TABLE 5

ICSOS RESULTS

speed knots	plant K	plant T	weighting factor	controller gains K1	T1	T2	cost J min
16	.1084	90.36	16.796	.454616	90.3459	10.0215	340.864
23	.1556	64.67	8.128	.373171	64.6658	8.4640	139.9916
32	.2167	45.45	4.2	.318645	45.4475	7.0662	60.828

In each case the controller zero (1/T1) cancels the plant pole (1/T). Additional experiments consisting of inserting arbitrary numbers in the Nomoto equation and repeating the computer run indicated that this will always be true. That is, to minimize the cost the plant pole is cancelled and a new pole location determined with appropriately adjusted gain.

The simple controller of Equation 4.1 is an arbitrarily chosen structure. To determine the effects of more complex controllers three additional structures were chosen as shown in Figure 4.2. Each of these was used with the Nomoto second-order model for the ship at each of the indicated speeds. The results are shown in Tables 6, 7, and 8.

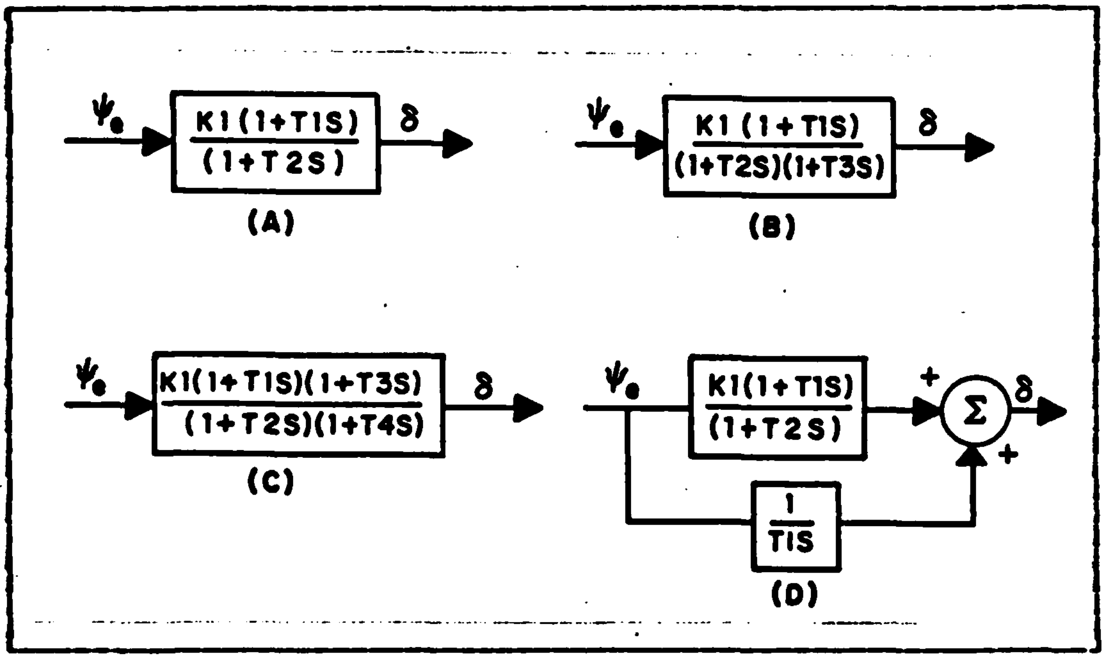

Figure 4.2 VARIOUS STRUCTURES FOR CONTROLLERS

These results are very interesting. At 16 knots the controller gain (K1), controller zero (1/T1) and controller pole (1/T2) are essentially the same for all structures. For structure B, which includes an additional pole, the function minimization subroutine tries to drive the additional pole to infinity, and no doubt would have done so if the calculations had continued. For structure C, which has two poles and two zeros, a zero and pole cancel indicating that they are not needed or wanted. For structure D, the integrator

TABLE 6

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS CONTROLLERS
FOR FIXED SHIP SPEED (16 KNOTS)
NOMOTO SECOND-ORDER MODEL (K=.1084,T=90.36)
λ = 16.796 , OPTIMAL PARAMETER GAINS OF
VARIOUS CONTROLLERS , COST FUNCTION

contr	controller gains						cost
	K1	T1	T2	T3	T4	Ti	J min
A	.454616	90.4359	10.0215	-	-	-	340.864
B	.444101	90.2950	9.8566	.01	-	-	341.046
C	.454511	90.3685	10.0224	23.085	23.084	-	340.864
D	.454581	90.3719	10.0222	-	-	1E09	340.864

TABLE 7

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS CONTROLLERS
FOR FIXED SHIP SPEED (23 KNOTS)
NOMOTO SECOND-ORDER MODEL (K=.1556,T=64.67)
λ = 8.128 , OPTIMAL PARAMETER GAINS OF
VARIOUS CONTROLLERS , COST FUNCTION

contr	controller gains					cost
	K1	T1	T2	T3	T4	J min
A	.373171	64.66579	8.463957	-	-	139.9916
B	.340024	79.65872	8.889204	.01	-	140.9338
C	.373139	64.66855	8.463497	25.9719	25.9738	139.9991

TABLE 8

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS CONTROLLERS
FOR FIXED SHIP SPEED (32 KNOTS)
NOMOTO SECOND-ORDER MODEL (K=.2167,T=45.45)
λ = 4.2 , OPTIMAL PARAMETER GAINS OF
VARIOUS CONTROLLERS , COST FUNCTION

contr	controller gains					cost
	K1	T1	T2	T3	T4	J min
A	.318645	45.44747	7.06617	-	-	60.828
B	.318	45.45	7.066	.05	-	60.933
C	.318678	45.57511	7.06790	50.1829	50.04832	60.828

gain is driven to zero. The same pattern of results is obtained at 23 knots and 32 knots. Note that in all cases the minimum cost is essentially the same, as would be expected since all controllers are the same.

Using the computer method of Figure 4.1 and the Nomoto third-order models of Table 1, controllers A, B, C of Figure 4.2 were optimized.. The results are shown in Tables 9, 10, and 11.

TABLE 9

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS CONTROLLERS
FOR FIXED SHIP SPEED (16 KNOTS)
NOMOTO THIRD-ORDER MODEL
(K=.073812,TZ=22.5673,TP1=12.9458,TP2=107.5853)
λ = 16.796 , OPTIMAL PARAMETER GAINS OF
VARIOUS CONTROLLERS , COST FUNCTION

contr	controller gains					cost
	K1	T1	T2	T3	T4	J min
A	0.6446104	90.0994	15.27712	-	-	370.4023
B	0.6441367	84.826	15.78691	.24598	-	374.3808
C	0.6151139	107.5782	8.73520	12.9368	24.9676	369.9297

TABLE 10

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS CONTROLLERS
FOR FIXED SHIP SPEED (23 KNOTS)
NOMOTO THIRD-ORDER MODEL
(K=.1067,TZ=15.675,TP1=9.014,TP2=75.13)
λ = 8.128 , OPTIMAL PARAMETER GAINS OF
VARIOUS CONTROLLERS , COST FUNCTION

contr	controller gains					cost
	K1	T1	T2	T3	T4	J min
A	0.5224258	63.13609	12.72212	-	-	152.2920
B	0.5216467	64.93709	12.63218	.0505174	-	152.5333
C	0.5001907	75.14852	6.527490	9.039928	18.260	152.2800

Of major interest is the fact that the difference in "cost" between A, B, C is less than one per cent. At each

TABLE 11

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS CONTROLLERS
FOR FIXED SHIP SPEED (32 KNOTS)
NOMOTO THIRD-ORDER MODEL
(K=.14771,TZ=11.2833,TP1=6.4699,TP2=53.7931)
λ = 4.2 , OPTIMAL PARAMETER GAINS OF
VARIOUS CONTROLLERS , COST FUNCTION

contr	controller gains K1	T1	T2	T3	T4	cost J min
A	0.427633	48.66C48	10.74485	-	-	68.09039
B	0.298732	89.40696	15.01033	.0597786	-	69.32355
C	0.417991	53.69561	4.970016	6.294354	13.85724	68.04735

speed (16,23,32 knots) controller C is "BEST", but the difference is slight. Examining the parameter values obtained for controller C, it is seen that at all three speeds both poles of the ship are essentially cancelled by zeros of the controller.

These results seem to indicate that the dynamics of the plant determines the optimum structure for the controller.

Using a state-feedback controller and Nomoto third-order models of Table 1, the controller was optimized for various ship speeds. Figure 4.3 shows the scheme used to evaluate the state-feedback controller.

Using the scheme of Figure 2.2, with no change in cost function or weighting, the optimal gains and costs were determined as shown in Table 12.

When comparing the state-feedback controller with controller C, it is seen that at each speed controller C has a lower cost. Among the controllers consired, controller C is "BEST" when using the Nomoto third-order model, although the differences in cost are not dramatic.

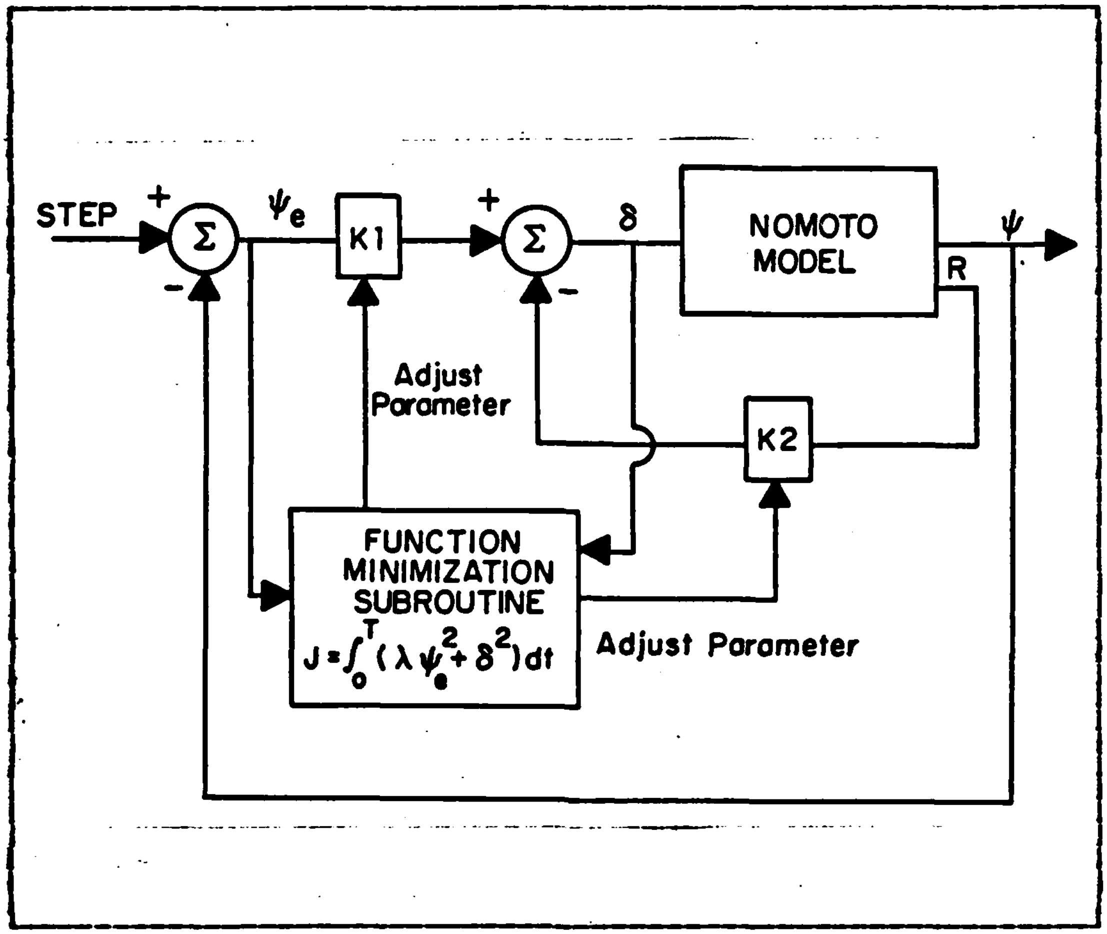

Figure 4.3 OPTIMIZATION OF STATE FEEDBACK CONTROLLER

TABLE 12

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS SHIP SPEEDS,
OPTIMAL PARAMETER GAINS FOR
STATE-FEEDBACK CONTROLLER

speed knots	Nomoto third-order plant K	TZ	TP1	TP2	weighting factor	controller K1	K2	cost J min
16	.0738	22.567	12.946	107.583	16.796	4.426	78.004	370.711
23	.1067	15.675	9.014	75.13	8.128	3.103	45.649	152.596
32	.1477	11.283	6.470	53.793	4.2	2.240	27.896	68.2513

V. CONTROLLER DESIGN USING FORTRAN PROGRAM

The Fortran program referenced in Chapter two which provided a computer simulation of the SL-7 ship was modified. A function minimization subroutine was coulped to the simulaticn and used the subroutine to adjust ccntrcller parameters to minimize the cost function and to evaluate the minimum cost. Figure 5.1 shows the scheme used to evaluate the contrcller parameters. This program was used for comparison to ICSOS. The computer program is shown in Appendix A.

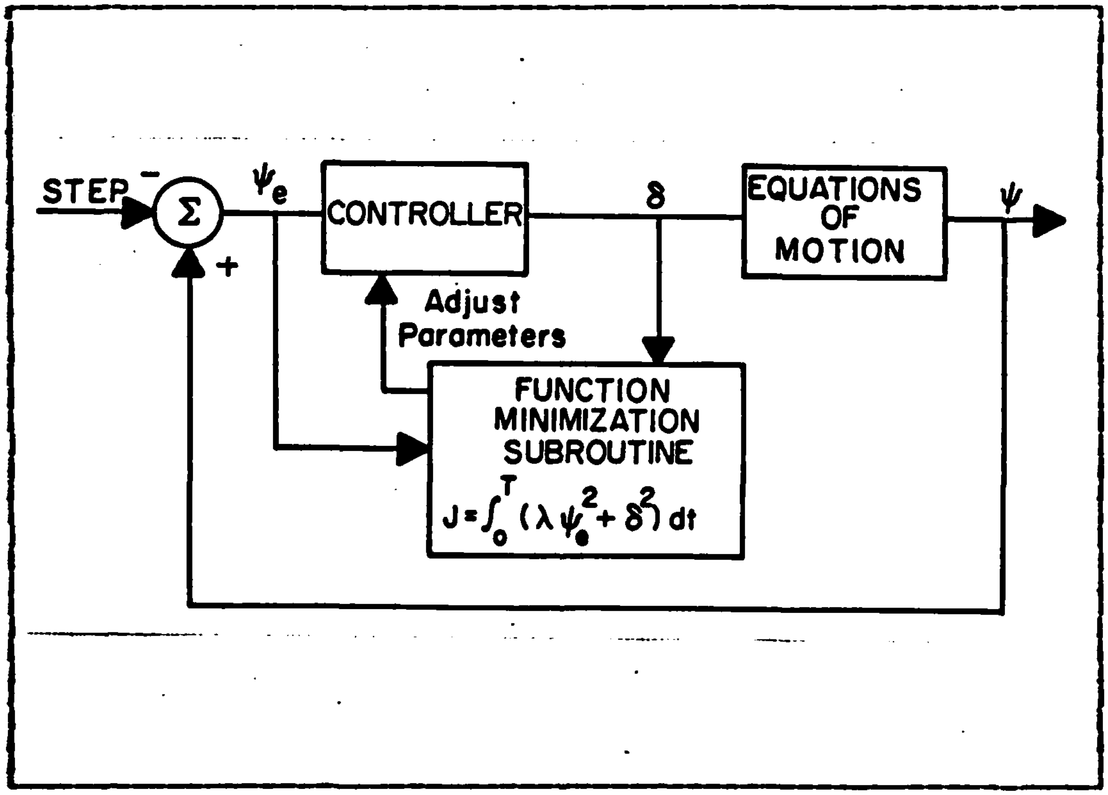

Figure 5.1 OPTIMIZATION OF CONTROLLER USING FORTRAN PROGRAM

Using the computer method of Figure 5.1 and the nonlinear equations of motion, controllers A, B, C of Figure 4.2 were optimized. The results are shown in Tables 13, 14, and 15.

TABLE 13

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS CONTROLLERS
FOR FIXED SHIP SPEED (16 KNOTS)
EQUATIONS OF MOTION
λ = 16.796 , OPTIMAL PARAMETER GAINS OF
VARIOUS CONTROLLERS , COST FUNCTION

contr	controller gains K1	T1	T2	T3	T4	cost J min
A	.648401	89.81704	15.381699	-	-	1.128189
B	.620050	90.67294	15.542297	0.9201336	-	1.173323
C	.617326	107.1494	8.597198	13.353928	25.21362	1.126307

TABLE 14

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS CONTROLLERS
FOR FIXED SHIP SPEED (23 KNOTS)
EQUATIONS OF MOTION
λ = 8.128 , OPTIMAL PARAMETER GAINS OF
VARIOUS CONTROLLERS , COST FUNCTION

contr	controller gains K1	T1	T2	T3	T4	cost J min
A	.522106	66.33122	12.83327	-	-	0.4640879
B	.495869	66.15152	13.01183	0.92783	-	0.4857854
C	.503967	74.79771	6.65880	9.20533	18.4022064	0.4636095

These results agree with those obtained by ICSOS and controller C provides the minimum cost.

If the assumption that the steering dynamics of the ship is adequately modeled as a second-order system is valid, then only two states are needed for feedback. For a third-order system three states are required. The controller structures are shown on Figure 5.2 and 5.3. Using the scheme

TABLE 15

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS CONTROLLERS
FOR FIXED SHIP SPEED (32 KNOTS)
EQUATIONS OF MOTION
λ = 4.2 , OPTIMAL PARAMETER GAINS OF
VARIOUS CONTROLLERS , COST FUNCTION

contr	controller gains					cost
	K1	T1	T2	T3	T4	J min
A	.428404	48.65540	10.814426	-	-	0.2072417
B	.298732	89.40696	15.010330	0.01	-	0.2118334
C	.417333	53.09654	5.096548	6.474857	14.0205	0.2071124

of Figure 5.1 with no change in cost function or weighting, the optimal gains and cost were determined as shown in Tables 16 and 17. Comparing costs, there is little difference between the two state system and the three state system. The comparison between state feedback with controller C, it is seen that at each speed controller C is better, but not much better.

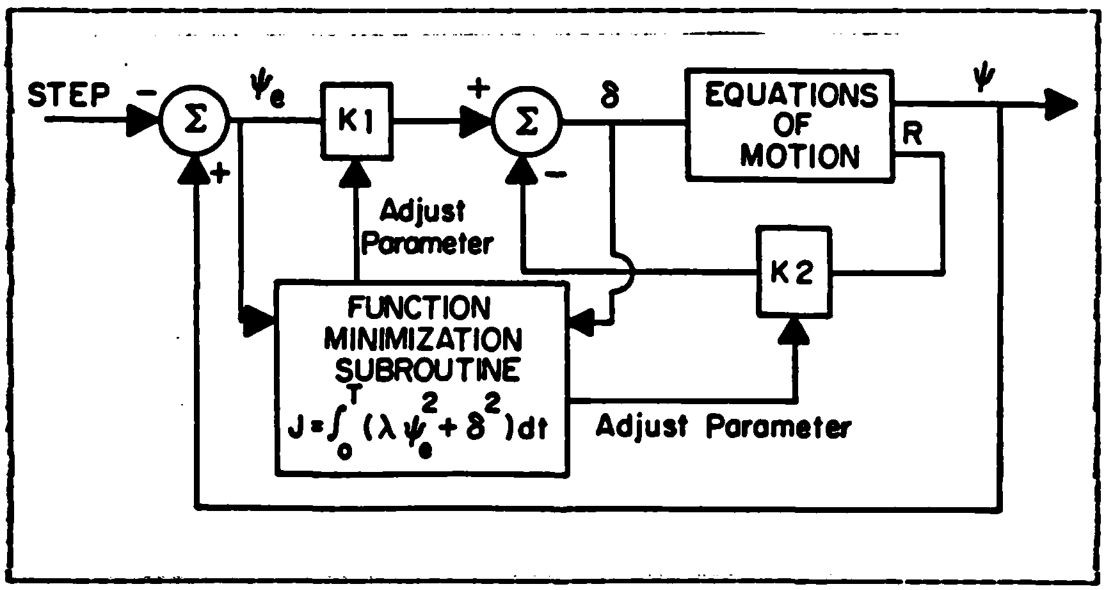

Figure 5.2 TWO STATE SYSTEM

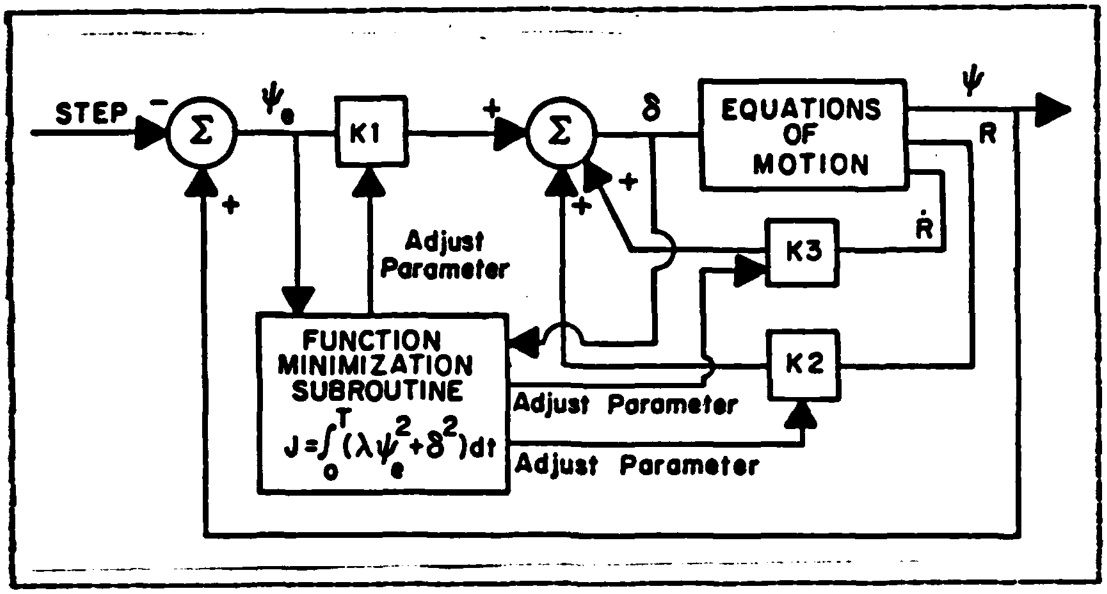

Figure 5.3 THREE STATE SYSTEM

TABLE 16

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS SHIP SPEEDS
EQUATIONS OF MOTION
OPTIMAL PARAMETER GAINS FOR
TWO STATE SYSTEM

speed knots	gains K1	K2	weighting factor	cost J min
16	4.4033689	77.5041656	16.796	1.128771
23	3.0889006	45.2637787	8.128	.4646050
32	2.2342062	27.6808014	4.2	.2075207

Note that for the Nomoto model studies yaw error and rudder angles were measured in degrees; when the equations of motion were simulated yaw error and rudder were in radians. Thus the numerical values of the cost, J, are different.

Transient response plots for controllers A, B, C, and three state-feedback at ship speed 32 knots are shown in Figures 5.4 - 5.9.

TABLE 17

SIMULATION RESULTS - STEADY STATE 600 SECS

CALM WATER FOR VARIOUS SHIP SPEEDS
EQUATIONS OF MOTION
OPTIMAL PARAMETER GAINS FOR
THREE STATE SYSTEM

speed knots	gains K1	K2	K3	weighting factor	cost J min
16	4.8617249	87.7073364	99.9802704	16.796	1.128289
23	3.6630983	56.2784882	88.5913391	8.128	.4643548
32	2.5967150	33.7511444	41.3186035	4.2	.2074225

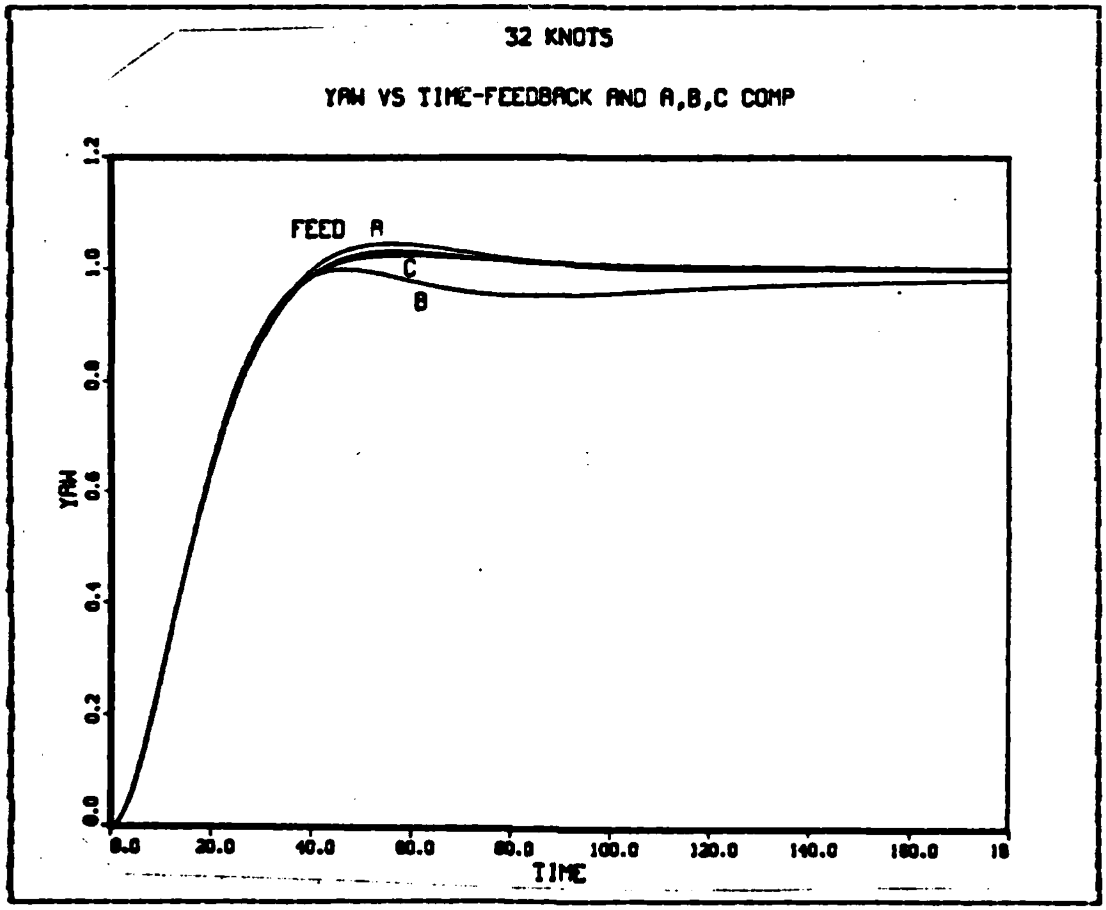

Figure 5.4 YAW vs. TIME (controller A, B, C and state-feedback)

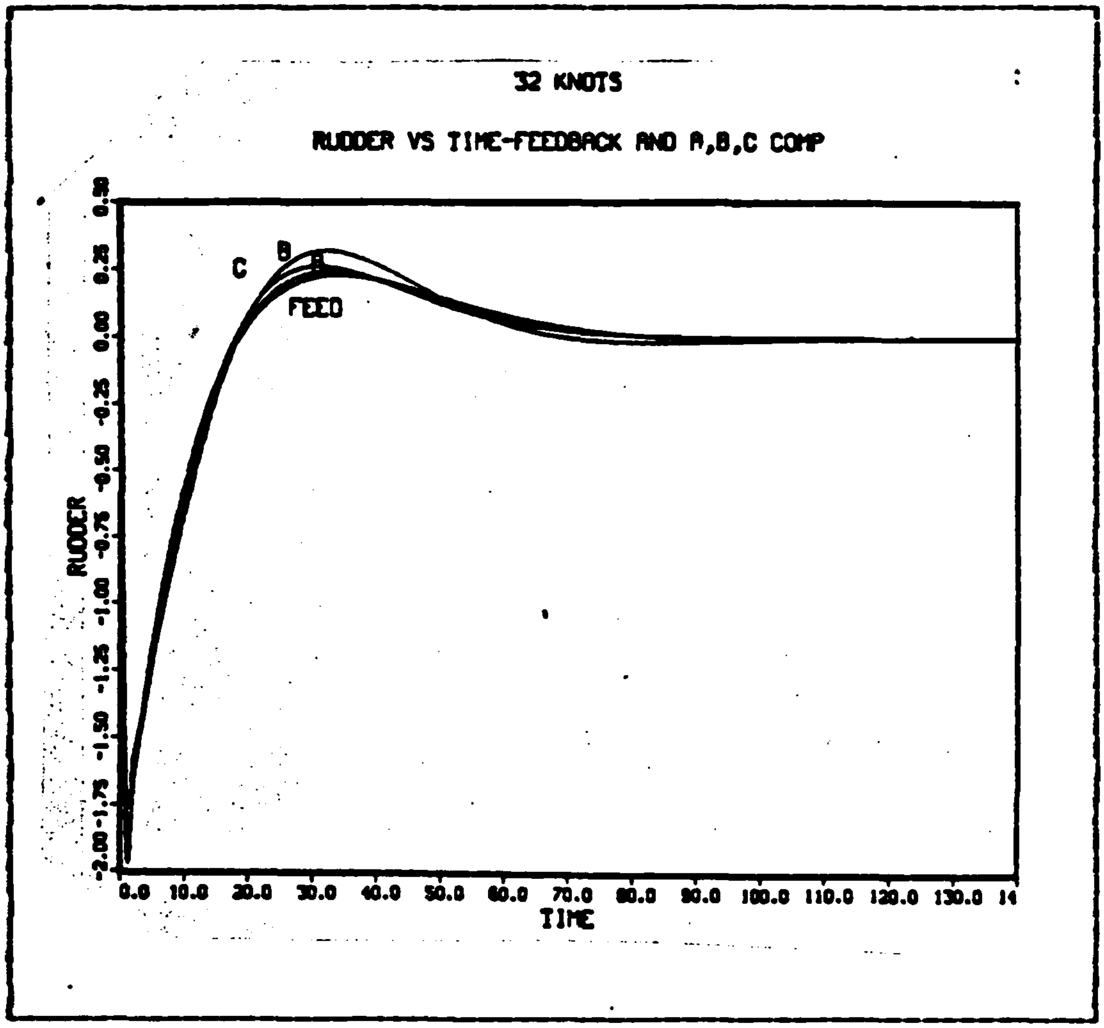

Figure 5.5 RUDDER vs. TIME (controller A, B, C and state-feedback)

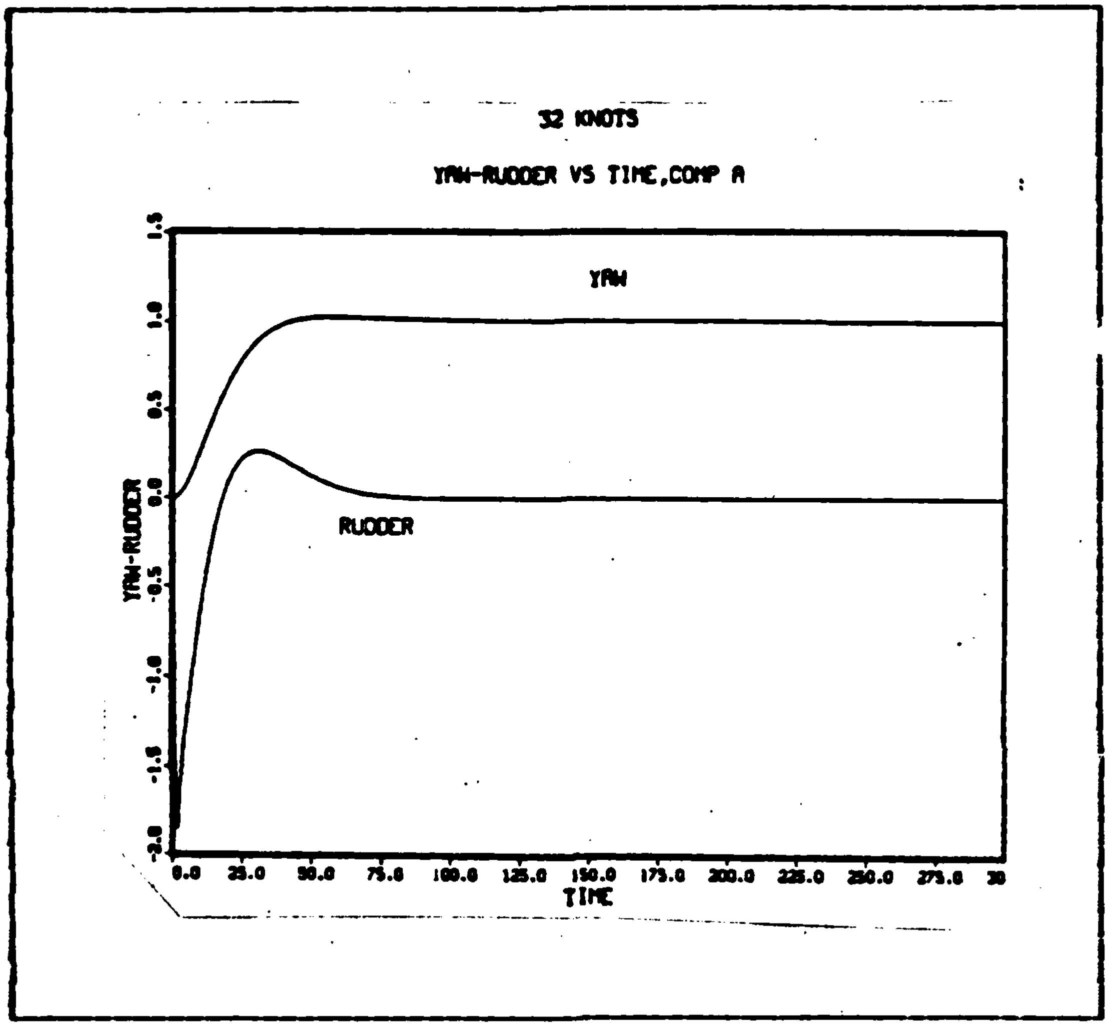

Figure 5.6 YAW AND RUDDER vs. TIME (controller A)

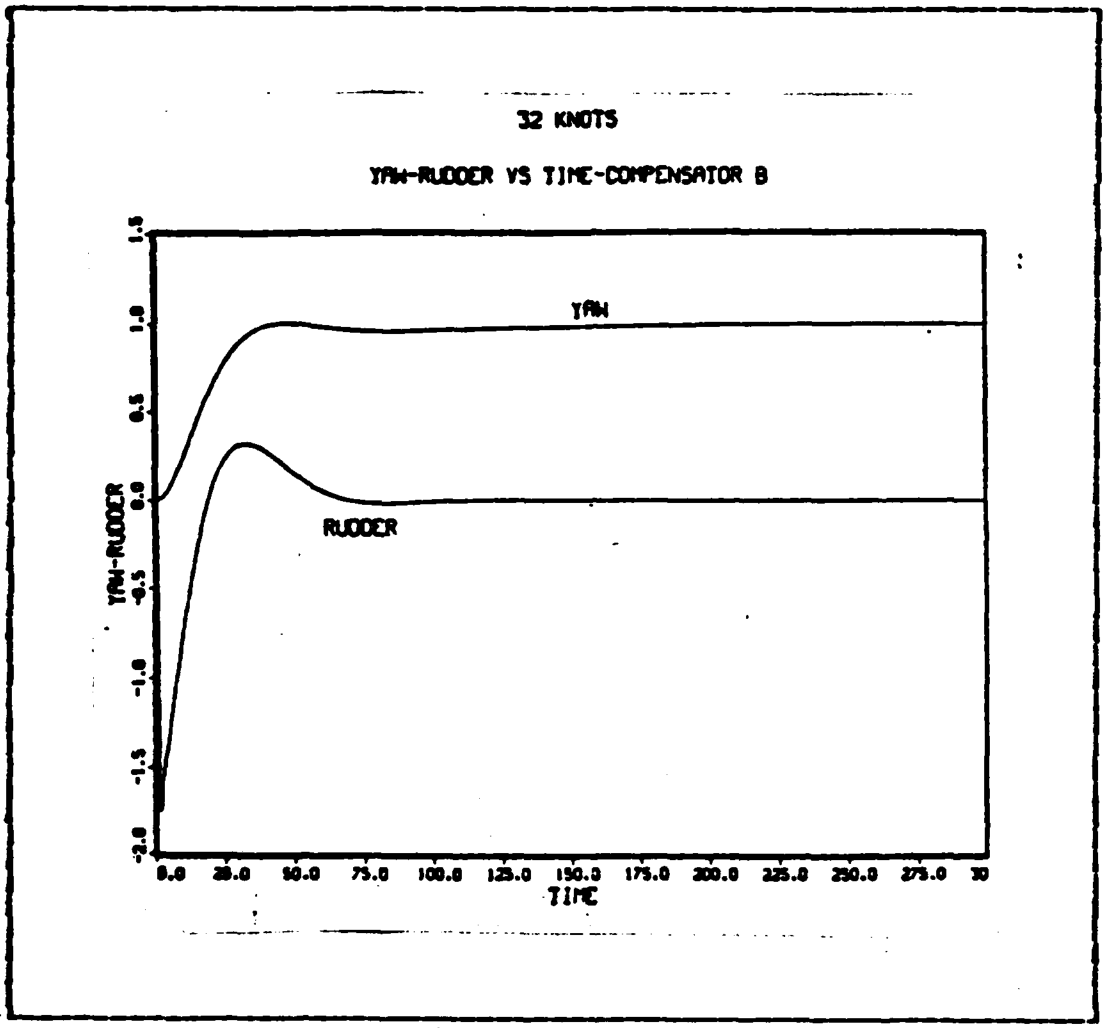

Figure 5.7 YAW AND RUDDER vs. TIME (controller B)

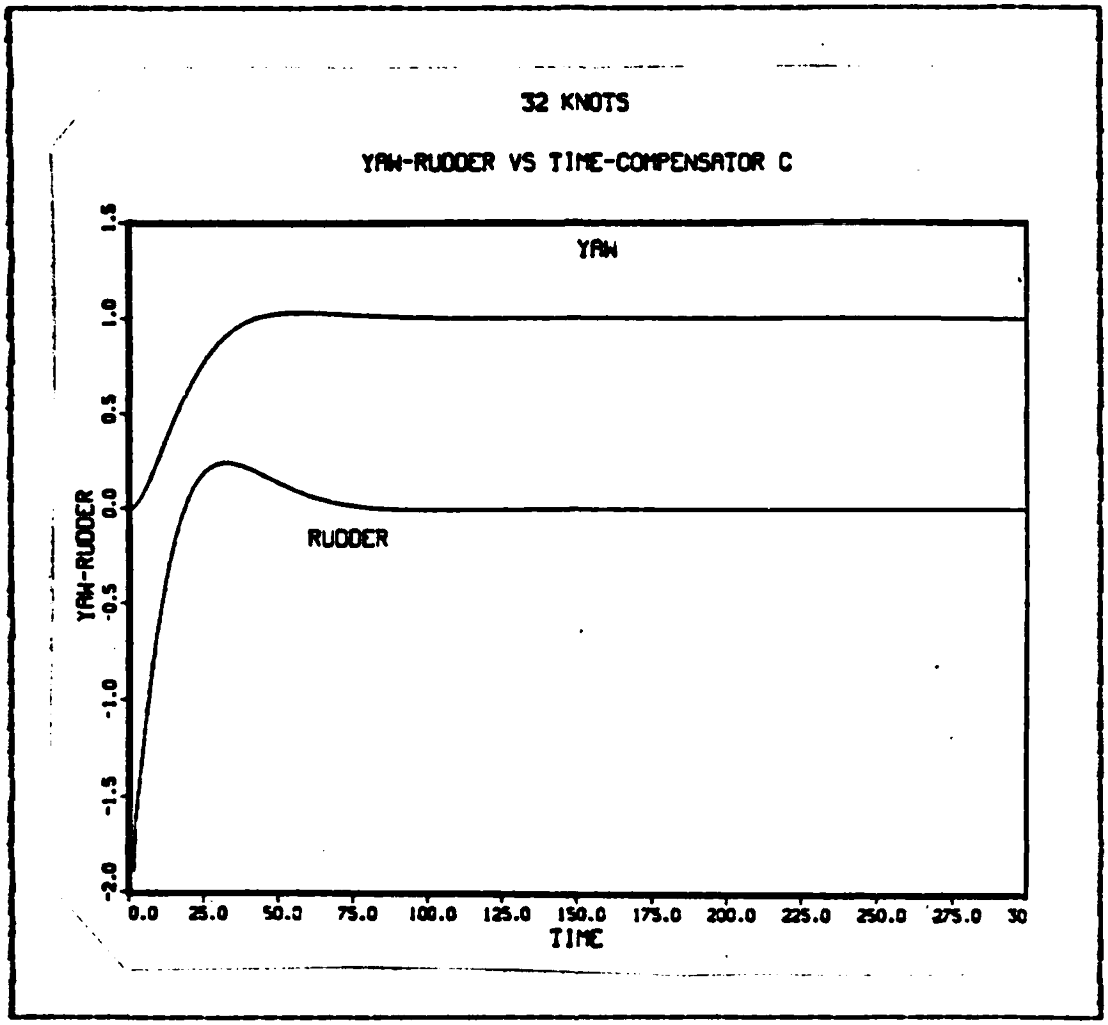

Figure 5.8 YAW AND RUDDER vs. TIME (controller C)

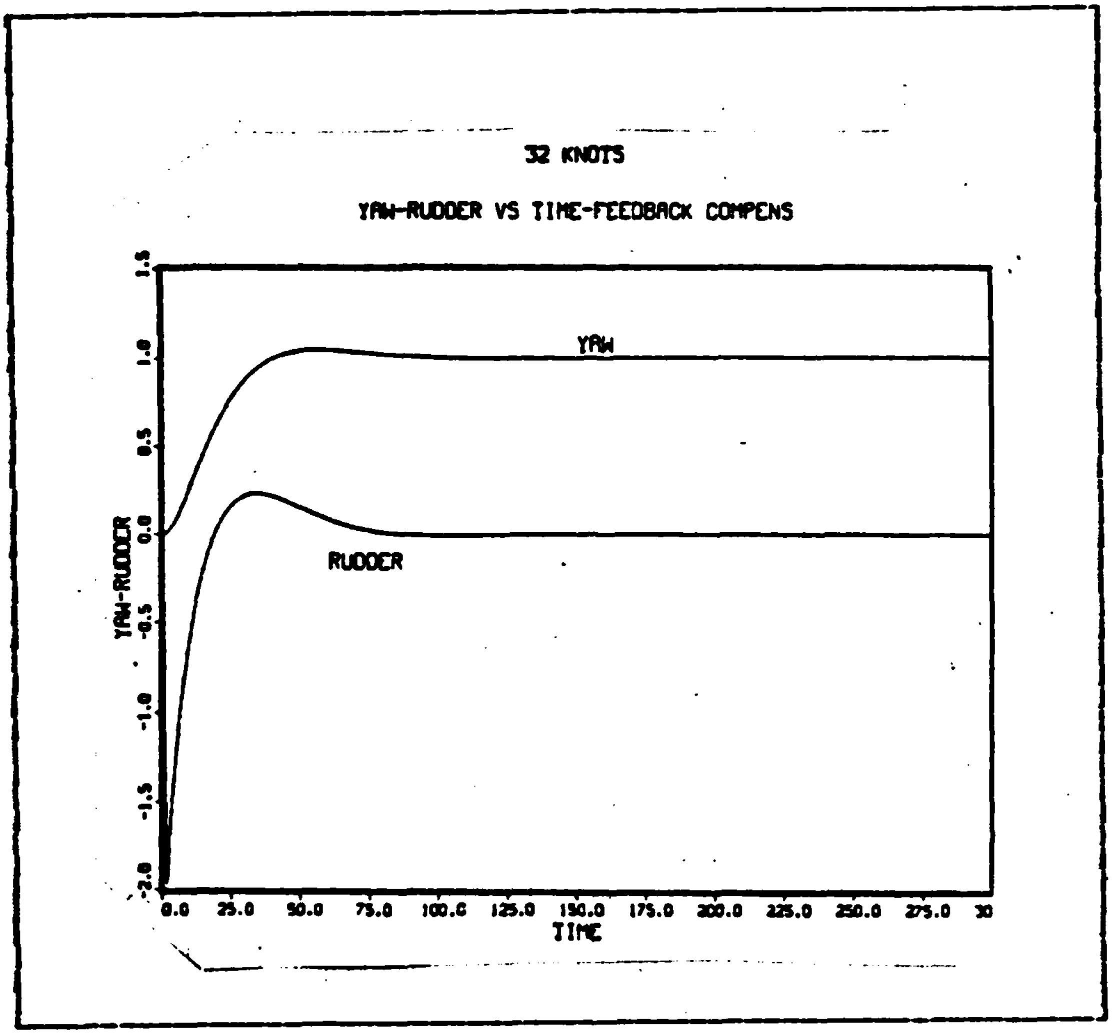

Figure 5.9 YAW AND RUDDER vs. TIME (state-feedback controller)

VI. CONTROLLER DESIGN IN SEA STATE

A sea state generator was coupled to the Fortran program, so that the function minimization subroutine could be used in the presence of the sea state. The sea state generator was an elaborate program obtained from DTNSRDC. This program generates added mass and inertia values as functions of encounter frequency and also calculates the forces and moments. The forces and moments are generated and stored in a look up table which was coupled to the equations of motion. Figure 6.1 shows the scheme used to evaluate the controller parameters. The computer program is shown in Appendix A.

The optimal gains obtained by the calm water study of Chapter five were use as the initial guess in evaluating the optimal controller parameters in the presence of a seaway. For comparison, studies of the value of the cost function using calm water gains in sea state were obtained; then the function minimization subroutine was allowed to adjust controller parameters in the presence of several sea states and encounter angles. The entire study was done at a ship speed of 32 knots. The added mass and inertia change with respect to encounter frequency as shown in Figures 6.2 and 6.3. Figure 6.3 is nondimensionalized by dividing the added inertia by the mass of the displaced water and the square of the length between perpendiculars. To convert back to dimensionalized units of lb-ft-sec^2, multiply the graph points by 2.581E12. Since the sea state is represented by irregular waves, the waves impinging on the ship hull contain the total energy density spectrum composed of many frequencies and the ship responds to an average value of added mass and inertia. The values used for this study was obtained at

encounter frequency of 0.75 rad/sec from our sea state generator. This frequency gave us values for added mass and inertia representative of an average value. The energy density spectra for various sea states are shown in Figure 6.4. The added mass for sway was changed from 2.6457E06 lb-sec^2/ft for calm water to 2.3043E06 lb-sec^2/ft for a seaway. The added moment of inertia for yaw was changed from 1.42E11 lb-ft-sec^2 for calm water to 1.5096E11 lb-ft-sec^2 for a seaway. All other hydrodynamic coefficients were kept constant at calm water values. The results are shown in Tables 18 - 25. In certain sea states and encounter angles the calm water optimal gains performed well as shown by calm water cost value when compared to sea state cost value. In most cases the function minimization subroutine found new gains with lower cost function values in seaway as compared to using calm water gains. In the calm water evaluation, the system was perturbed with a one degree course change, but the course change was not included in the seaway tests. The difference in cost values is attributed to the difference in operating conditions.

Using the Proportional, Integral and Derivative (PID) controller Equation 6.1 with no change in cost function, the function minimization subroutine was used to adjust controller parameters to minimize the cost function and evaluate the minimum cost. The results are shown in Table 26. When comparing the PID with controller A, it is seen that at each encounter angle, controller A is better. These results agree that in a seaway controller A provides the minimum cost.

Table 27 shows comparison of the minimum cost function for controller A, controller C, and PID. The study was done at ship speed of 32 knots and at sea state 4. Controller A provides the minimum cost.

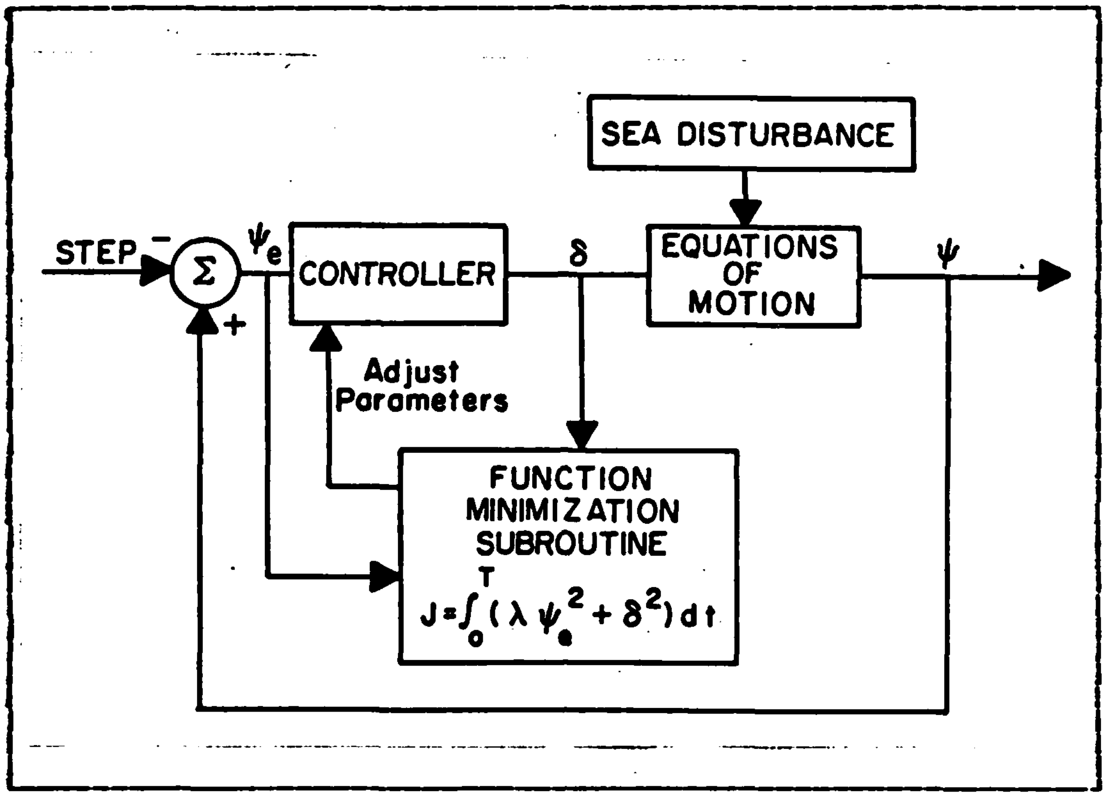

Figure 6.1 OPTIMIZATION OF CONTROLLER IN SEA STATE

The optimal gains obtained in the presence of sea state was done over using a simulating time of 600 seconds. The sea state program is designed to provide gradual increase in the forces and moments during an initial time interval. This is done to minimize initial condition transients in the ship dynamics. There will unavoidably be some transient effects, however, and these could affect the value of the cost, J, determined during the 600 seconds of simulation. To determine whether such initial transients had any significant contribution to the value of J, additional simulation runs were made with the controller parameters fixed at their optimal values. However, evaluation of the cost, J, was started only after 300 seconds of simulation had elapsed.

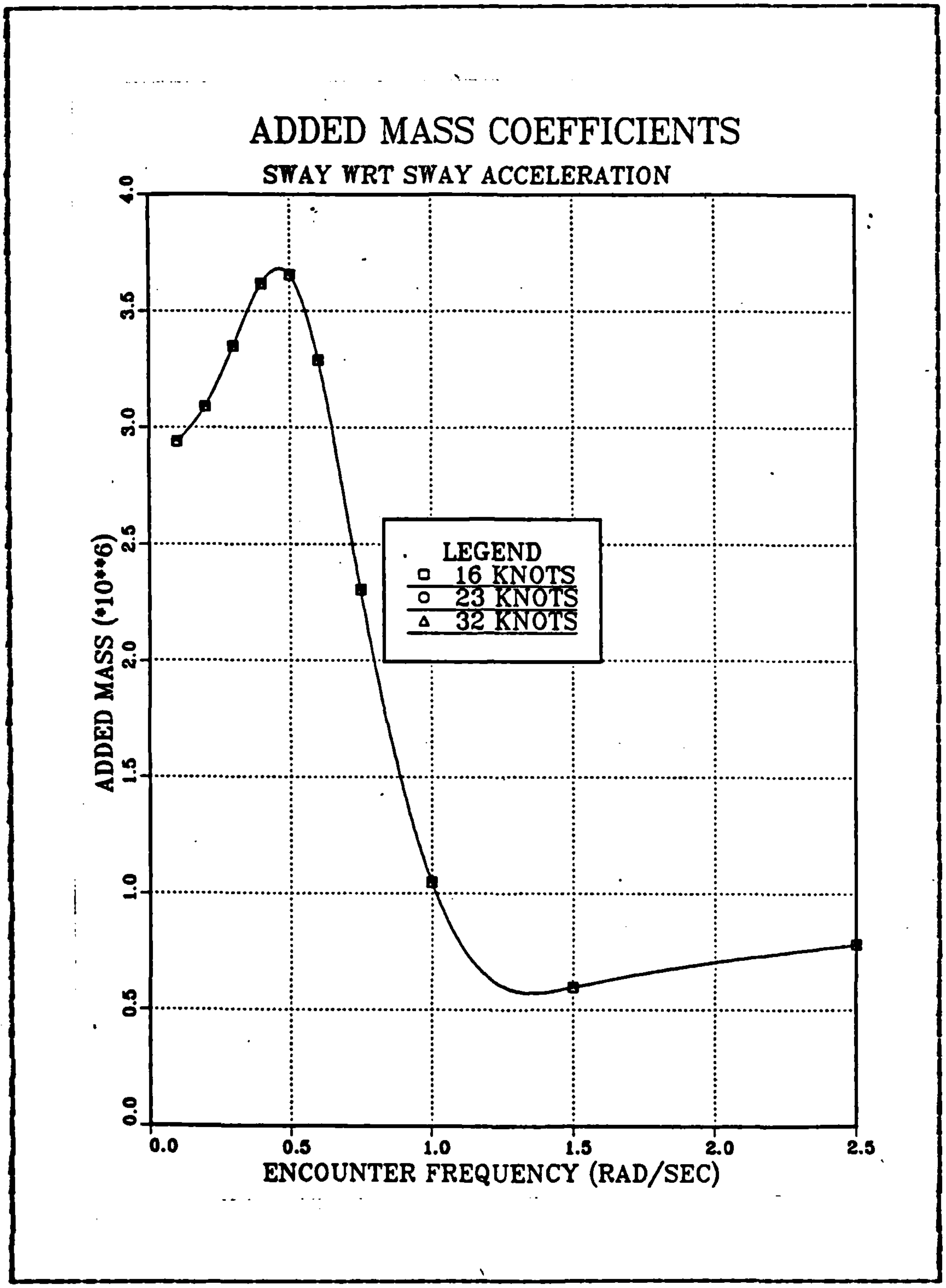

Figure 6.2 ADDED MASS vs. ENCOUNTER FREQUENCY

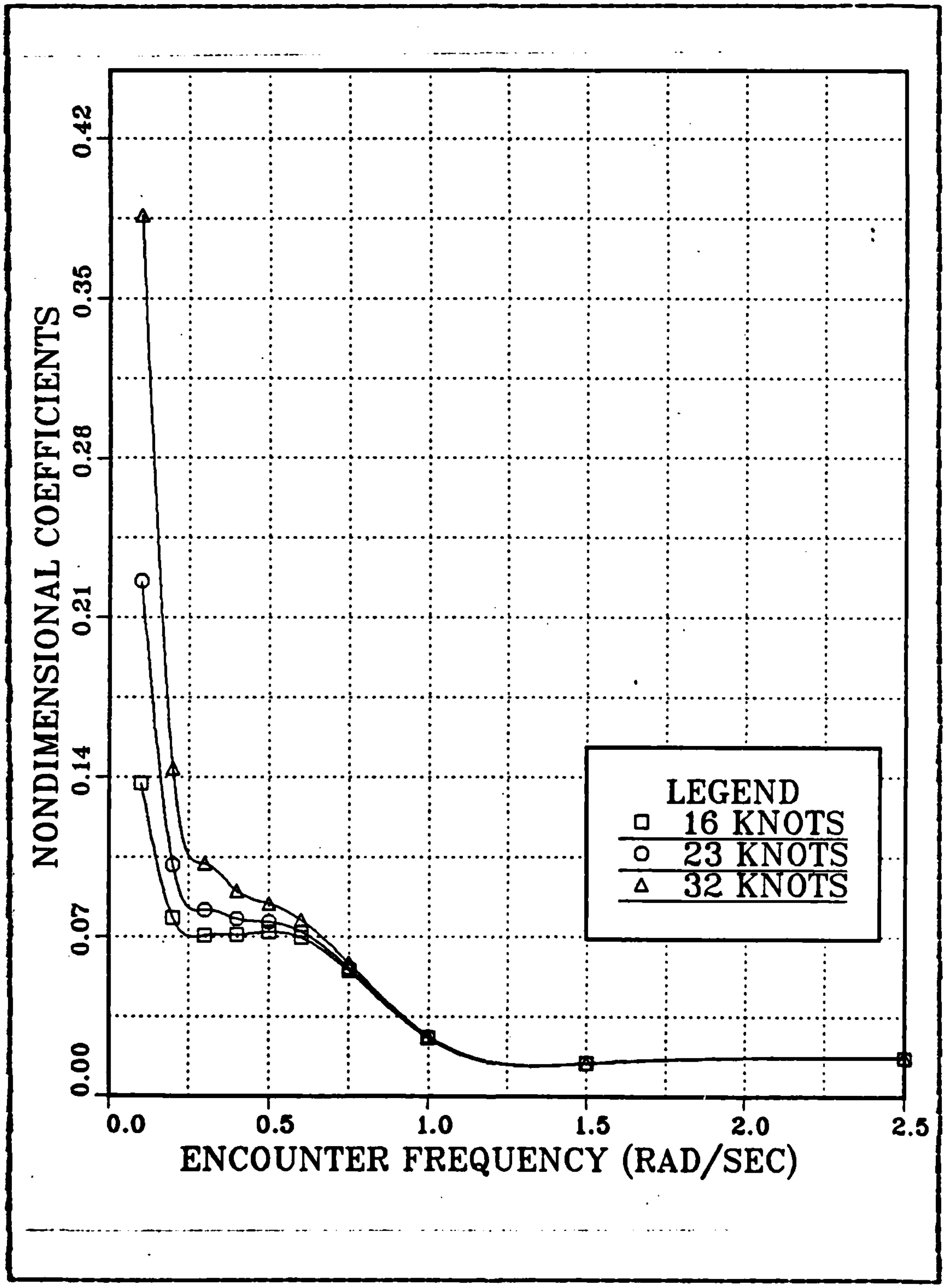

Figure 6.3 ADDED INERTIA vs. ENCOUNTER FREQUENCY

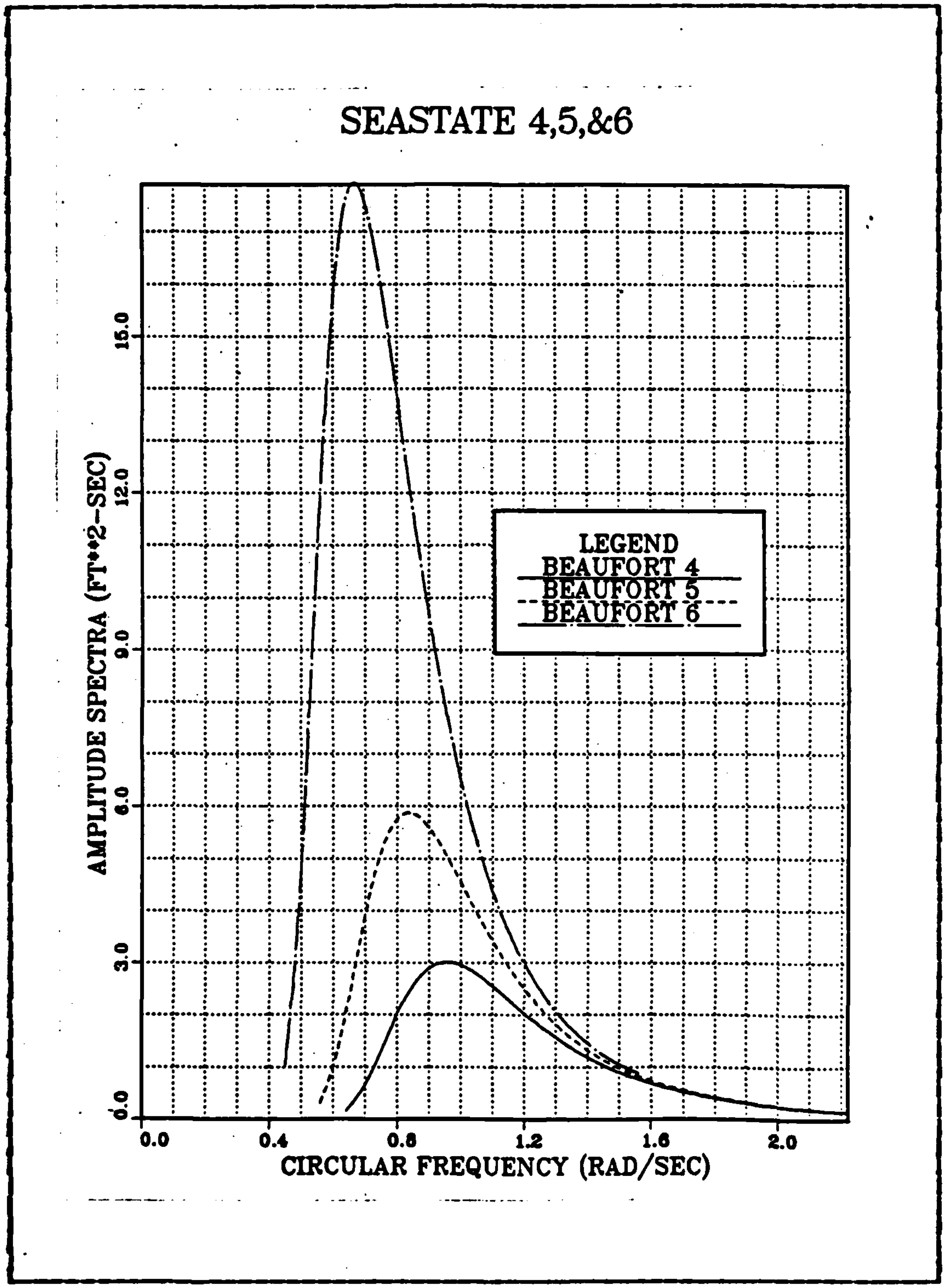

Figure 6.4 ENERGY DENSITY SPECTRUM

TABLE 18

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0

SEA STATE 1

CONTROLLER A

encounter angle degree	controller gains K1	T1	T2	sea state cost J min	cost with calm water J
0	.4284037	48.6554395	10.814426	.61745E-34	.61745E-34
30	1.1561117	29.3693695	1.4592390	.2870198	.5128402
60	1.4033298	10.6530075	1.1086683	.1342071	.2154726
90	.2969198	58.2413940	1.8758221	.1300669	.1565958
120	.1761794	299.999512	30.7967834	.05741726	.0727727
150	2.8430557	5.2826872	.8887696	.0219070	.0939400
180	1.6211386	14.0782928	2.0712433	.0051925	.0095694

TABLE 19

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0

SEA STATE 2

CONTROLLER A

encounter angle degree	controller gains K1	T1	T2	sea state cost J min	cost with calm water J
0	.42840370	48.6554395	10.814426	.61745E-34	.61745E-34
30	.27997030	249.935059	19.857742	.04774852	.0886225
60	.95575100	24.3813629	2.3079853	.04104504	.0535879
90	1.3577642	9.49564080	1.1068363	.02650556	.0483197
120	1.1208973	25.4498596	4.0224676	.04928402	.0717524
150	2.9777727	16.2154541	.56274800	7.5751530	28.1294403
180	.61420630	.482041200	6.2521963	.000124338	.0002445

TABLE 20

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0

SEA STATE 4

CONTROLLER A

encounter angle degree	controller gains K1	T1	T2	sea state cost J min	cost with calm water J
0	.4284037	48.65540	10.814426	.620598E-34	.620598E-34
30	.9815440	5.733036	.6999879	.02854677	.0395892
60	.6201209	40.80556	19.606873	.09375697	.1032696
90	1.809746	36.01225	6.324708	1.5171340	4.1623011
120	5.195190	18.92513	.6999907	9.991730	48.970703
150	1.446776	16.89375	.5265408	16.67052	24.822098
180	.1000000	1.000000	20.149999	.00739631	.0076657

TABLE 21

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0

SEA STATE 6

CONTROLLER A

encounter angle degree	controller gains K1	T1	T2	sea state cost J min	cost with calm water J
0	.4284037	48.6553955	10.8144264	.50899E-32	.50899e-32
30	2.9715786	10.4721832	.5342450	1.4287940	4.74724010
60	1.7228041	8.4014740	.5141125	1.5827220	3.42744920
90	1.8584366	37.1672655	.5792384	4.5505371	13.2757149
120	3.3422489	106.722259	.9260592	22.108002	94.5497589
150	.2854474	157.483887	119.981018	.81100580	1.50448510
180	.8053379	.75733550	6.04484460	.07365978	.14256400

TABLE 22

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0

SEA STATE 1

CONTROLLER C

encounter angle degree	controller gains K1	T1	T2	T3	T4	sea cost J min	calm cost J
0	1.61345	16.8755	25.0481	47.3405	1.73759	.14E-33	.45E-33
30	.957558	12.6178	7.32113	43.3531	8.15752	.324739	.357733
60	.781984	17.6475	9.22485	13.9438	16.7663	.159710	.203137
90	.417332	53.0965	5.09655	6.47857	14.0205	.148588	.148588
120	.417332	53.0965	5.09655	6.47857	14.0205	.077918	.077918
150	2.13735	18.8265	17.5778	25.1516	21.1481	.031496	.081612
180	.957558	12.6178	7.32113	43.3531	8.15752	.006566	.008172

TABLE 23

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0

SEA STATE 2

CONTROLLER C

encounter angle degree	controller gains K1	T1	T2	T3	T4	sea cost J min	calm cost J
0	.417333	53.0965	5.09655	6.47486	14.0205	.18E-33	.18E-33
30	.849594	19.9913	9.34138	20.3578	13.7487	.054338	.061184
60	.417333	53.0965	5.09655	6.47486	14.0205	.044536	.044536
90	.781984	17.6475	9.22485	13.9438	16.9438	.033518	.048467
120	.880395	21.4597	10.9255	9.24547	11.0667	.055292	.056288
150	.899999	15.7103	1.11632	41.3275	2.29012	10.7636	23.8522
180	.440916	.093671	17.7305	25.2103	5.04178	.000125	.001635

TABLE 24

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0

SEA STATE 4

CONTROLLER C

encounter angle degree	controller gains K1	T1	T2	T3	T4	sea cost J min	calm cost J
0	1.22424	70.3578	61.3016	10.5467	61.8215	.62E-34	.14E-33
30	.690573	20.1488	20.3214	5.10369	19.7841	.034033	.071978
60	.782547	12.6178	13.7713	21.5637	21.5637	.098914	.244369
90	2.22895	51.7744	54.3190	17.3522	6.07814	1.57368	2.98305
120	3.72749	85.4697	40.6999	8.52234	1.35207	10.3530	37.8988
150	.417333	53.0965	5.09655	6.47486	14.0205	20.3956	20.3956
180	.059166	.286208	19.5103	46.4767	22.3286	.007397	.099413

TABLE 25

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0

SEA STATE 6

CONTROLLER C

encounter angle degree	controller gains K1	T1	T2	T3	T4	sea cost J min	calm cost J
0	2.33178	52.0881	95.7892	31.6564	11.6959	.49E-32	.19E-31
30	2.08709	73.1270	76.7193	12.1726	16.4711	2.00375	3.83379
60	2.00128	71.6612	77.6750	13.1170	17.0912	2.15428	3.41794
90	.957558	12.6178	13.7713	72.0670	15.4611	5.76399	8.80971
120	3.10589	81.8044	38.2439	91.2237	9.14683	24.9099	72.6716
150	1.51250	70.3578	61.3016	35.5894	61.8215	2.50971	7.50022
180	1.52875	1.87828	43.4698	49.9147	11.2599	.078894	.930885

TABLE 26

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0

SEA STATE 4

PID CONTROLLER

encounter angle	controller gains K1	T1	T2	sea state J min
30	.95263100	4.20720860	.69368610	.02985619
60	.68631890	12.5794449	8.2121658	.09730512
90	2.5809155	12.4247589	.77810380	1.5915950
120	4.9198265	12.5986176	.67592390	10.708980
150	1.3970823	15.7682953	.51991180	17.427200

$$\delta(S)/\psi_\epsilon(S) = K1 + K1*T1*S / (1+T2*S)**2 \qquad (6.1)$$

TABLE 27

COMPARISON OF THE MINIMUM COST

SHIP SPEED (32 KNOTS)
SEA STATE 4

encounter angle degree	controller A J min	controller C J min	controller PID J min
30	.02854677	.034033	.02985619
60	.09375697	.098914	.09730512
90	1.5171340	1.57368	1.5915950
120	9.9917300	10.3530	10.708980
150	16.670520	20.3956	17.427200

The value obtained was then doubled and compared with the result of evaluating J over the full 600 seconds. Comparison of Table 28 with cost values in Tables 18, 19, 20, 21 shows only small differences.

To obtain insight into the stochastic process of irregular seas, a deterministic process was studied. The Fortran

TABLE 28

EFFECTS DUE TO TRANSIENT AND GRADUAL BUILD UP OF SEA STATE

INTEGRATION OF COST FUNCTION (300 TO 600 SECS)
FIXED SHIP SPEED (32 KNOTS) IN A SEAWAY

sea state	encounter angle	controller gains K1	T1	T2	cost J min	cost 2*J min
1	60	1.4033298	10.650075	1.1086683	.0641122	.1282244
2	60	.95575100	24.381363	2.3079853	.0199731	.0399462
4	60	.62012090	40.805560	19.606873	.0515974	.1031948
6	60	1.7228041	8.4014740	.51411250	.7906179	1.581236

program was modified to minimize the cost function in the presence of a regular sea. To allow comparison with previous work the encounter frequency of 0.75 rad/sec was used and scaled the amplitude of the regular sea to its prospective sea state. The entire study was done at a ship speed of 32 knots. The results are shown in Tables 29, 30, and 31.

Table 29 shows that for regular seas the controller parameters do not change significantly for different sea states; but as sea state increases, the cost value increases due to the increase in yaw moment and sway force on the ship. Tables 30 and 31 also show that the controller parameters do not change significantly from sea state to sea state. However, an encounter angle of 90 degrees shows a relatively high cost compared to costs calculated for 60 and 120 degrees at a given sea state. To account for this anomaly, the following is suggested. In the regular sea, the added mass and inertia were known for a given encounter frequency, while in the irregular sea a representive average value was used. The method used to obtain the average might not represent the actual average. Also, it seems reasonable to suppose, that the assumptions of the function weighting factor are satisfied for all encounter angles; that is, the weighting function (Eq. 3.2), which appears in the cost

function (Eq. 3.1), does totally represent the added drag for all encounter angles. Future study is needed to answer these questions.

The sea state in the deterministic model is represented by regular waves. On this description, the waves impinging on the ship hull correspond to only one frequency in the energy density spectrum. In the case of irregular seas, however, the spectral components change for different states, as shown in Figure 6.4. Thus comparison of the controller parameters obtained for regular seas with results for irregular seas is not justified. The function minimization subroutine adjusted controller parameters to minimize the cost function for either case (irregular or regular seas) as shown in tables 32 and 33.

TABLE 29

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A REGULAR SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0
ENCOUNTER FREQUENCY = 0.75 RAD/SEC
ENCOUNTER ANGLE = 60 DEGREES

CONTROLLER A

sea state	controller gains K1	T1	T2	cost J min
1	.1449795	141.383179	32.9405670	.000764582
2	.1534657	129.987473	31.4042358	.003056434
4	.1514665	135.798737	32.9749756	.009345479
6	.1533340	135.488495	33.5585632	.022174600

Note that in both the deterministic and stochastic models, among the controllers considered, controller A is "BEST" in a seaway disturbance, although the differences in cost are not dramatic.

Finally, the observed dependence of optimal controller gains on sea state and encounter angle suggests that an

TABLE 30

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A REGULAR SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0
ENCOUNTER FREQUENCY = 0.75 RAD/SEC
SEA STATE 4

CONTROLLER A

encounter angle	controller gains K1	T1	T2	cost J min
30	.2351043	102.021973	28.3396912	.002985300
60	.1514665	135.798737	32.9749756	.009345479
90	.4964442	66.546493	49.7598267	.048143090
120	.1327230	149.540543	33.6013489	.038937880
150	.4536914	70.566528	31.5839539	.062534153

TABLE 31

SIMULATION RESULTS - STEADY STATE 600 SECS

FIXED SHIP SPEED (32 KNOTS) IN A REGULAR SEAWAY
SHIP MODEL: EQUATIONS OF MOTION
YAWC=0.0
ENCOUNTER FREQUENCY = 0.75 RAD/SEC
SEA STATE 6

CONTROLLER A

encounter angle	controller gains K1	T1	T2	cost J min
30	.2370022	100.122940	28.0581207	.007092878
60	.1533340	135.488495	33.5585632	.022174600
90	.5210407	62.153702	49.9858093	.112772880
120	.1414837	142.695160	35.3171234	.091541650
150	.4587426	71.451385	33.4568024	.144615829

adaptive controller must be used to provide a continuous minimum on the cost function.

After obtaining the optimal gains for controller A, to observe the behavior of the rudder and yaw motion of the ship, transient response plots were obtained for controller A at ship speed of 32 knots and sea state 4 for various encounter angles as shown in Figures 6.5 - 6.14. Note the

TABLE 32

COMPARISON OF IRREGULAR TO REGULAR SEAS CONTROLLER GAINS

SEA STATE 4

CONTROLLER A

encounter angle		controller gains K1	T1	T2
30	(irregular)	.9815440	5.733036	.6999879
30	(regular)	.2351043	102.021973	28.3396912
60	(irregular)	.6201209	40.805560	19.6068730
60	(regular)	.1514665	135.798737	32.9749756
90	(irregular)	1.809746	36.012250	6.3247080
90	(regular)	.4964442	66.546493	49.7598267
120	(irregular)	5.195190	18.925130	.6999907
120	(regular)	.1327230	149.540543	33.6013489
150	(irregular)	1.446776	16.893750	.52654C8C0
150	(regular)	.4536914	70.566528	31.5839539

TABLE 33

COMPARISON OF IRREGULAR TO REGULAR SEAS CONTROLLER GAINS

SEA STATE 6

CONTROLLER A

encounter angle		controller gains K1	T1	T2
30	(irregular)	2.9715786	10.4721832	.5342450
30	(regular)	.23700220	100.122940	28.05812C7
60	(irregular)	1.7228041	8.4014740	.5141125
60	(regular)	.15333400	135.488495	33.5585632
90	(irregular)	1.8584366	37.1672655	.5792384
90	(regular)	.5210407	62.153702	49.9858093
120	(irregular)	3.3422489	106.722259	.9260592
120	(regular)	.1414837	142.695160	35.3171234
150	(irregular)	.2854474	157.483887	119.981018
150	(regular)	.4587426	71.451385	33.4568024

increase in both rudder and yaw amplitude as the encounter angle increased. This is due to the increase in yaw moment and sway force on the ship.

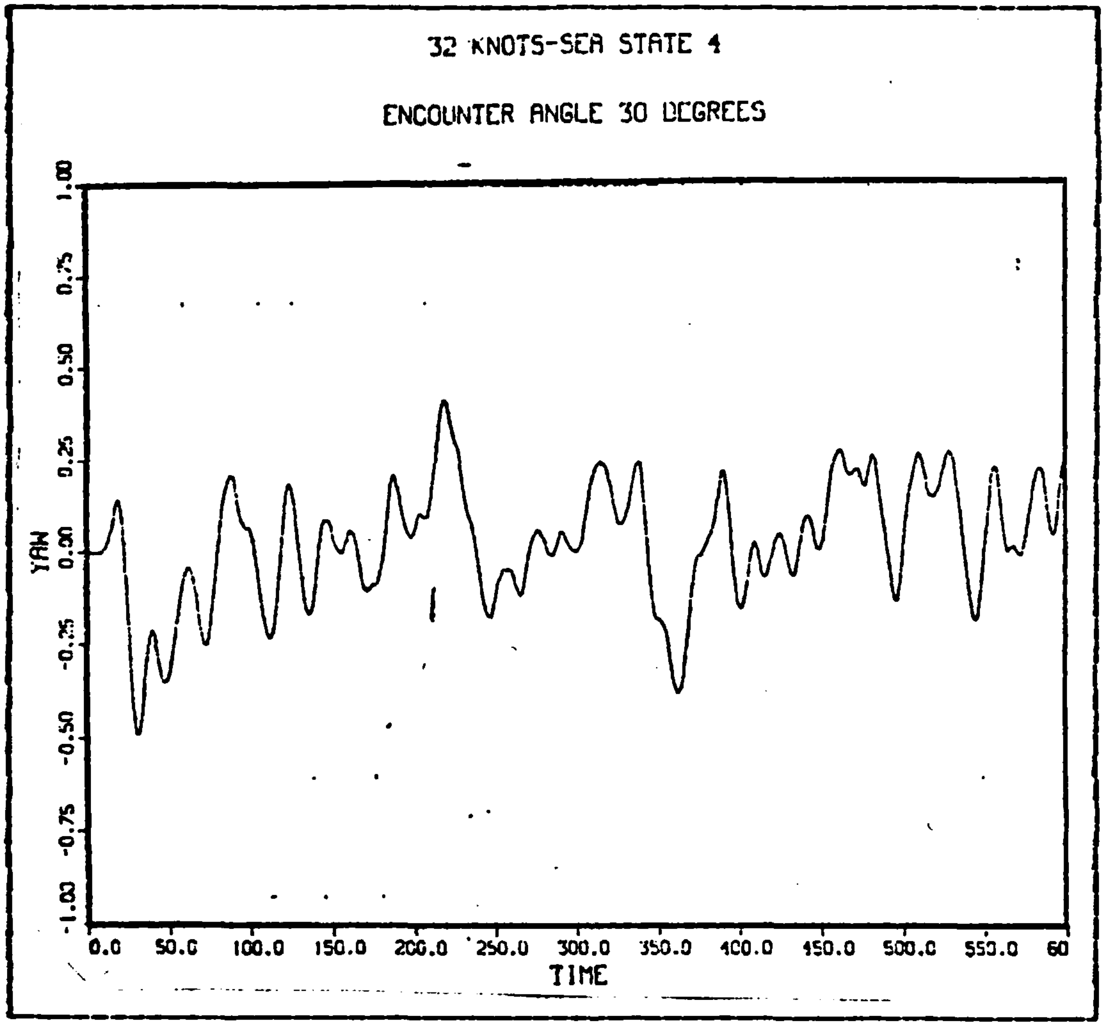

Figure 6.5 YAW vs. TIME 30 DEGREES

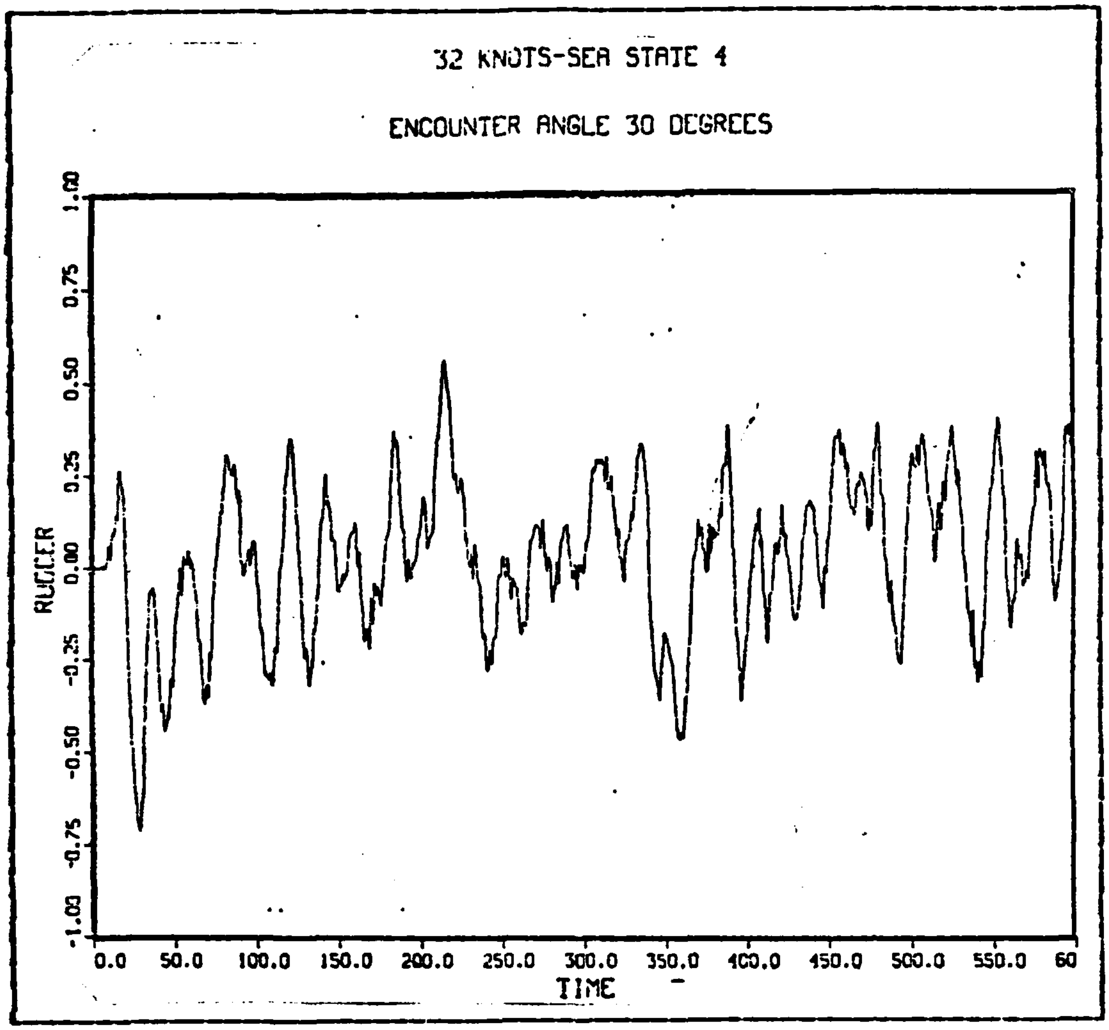

Figure 6.6 RUDDER vs. TIME 30 DEGREES

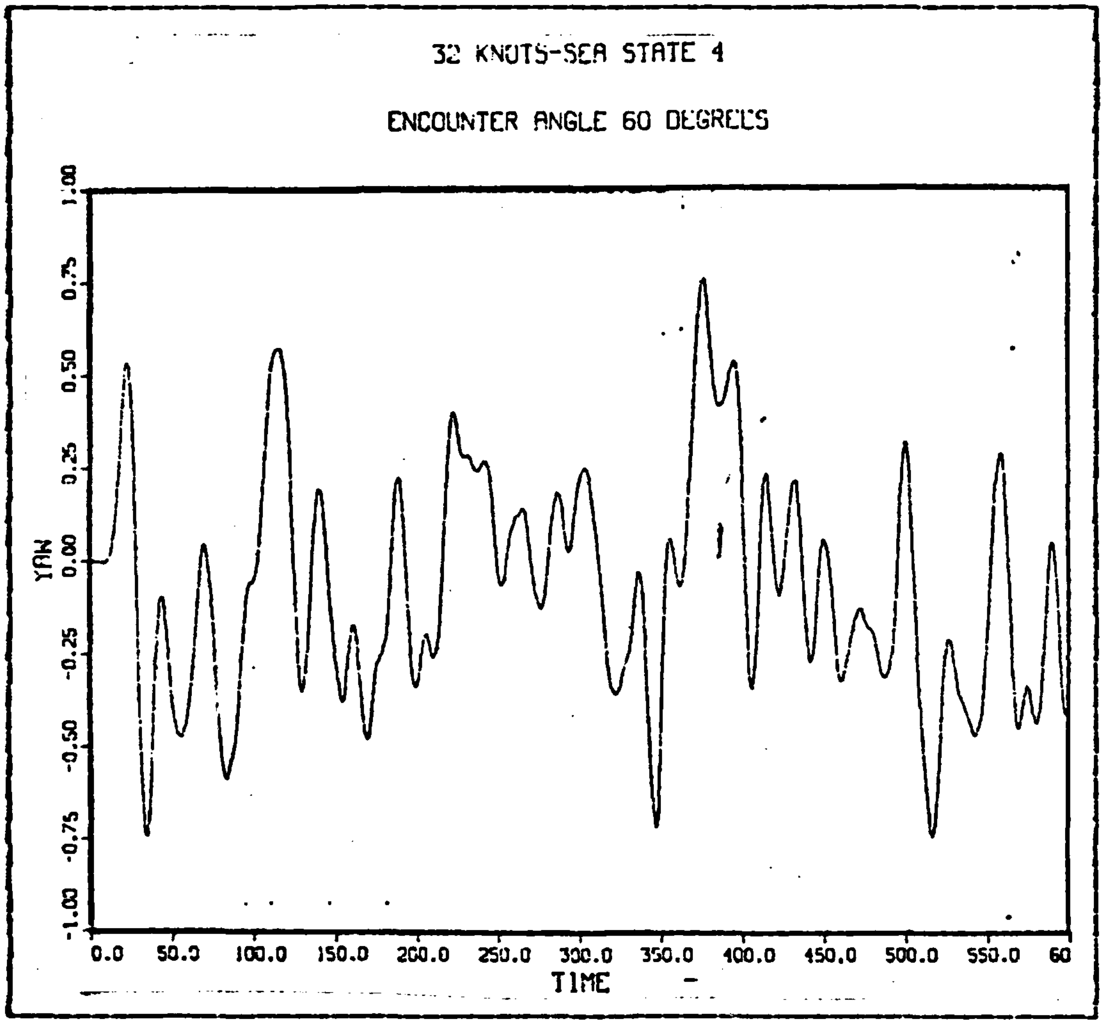

Figure 6.7 YAW vs. TIME 60 DEGREES

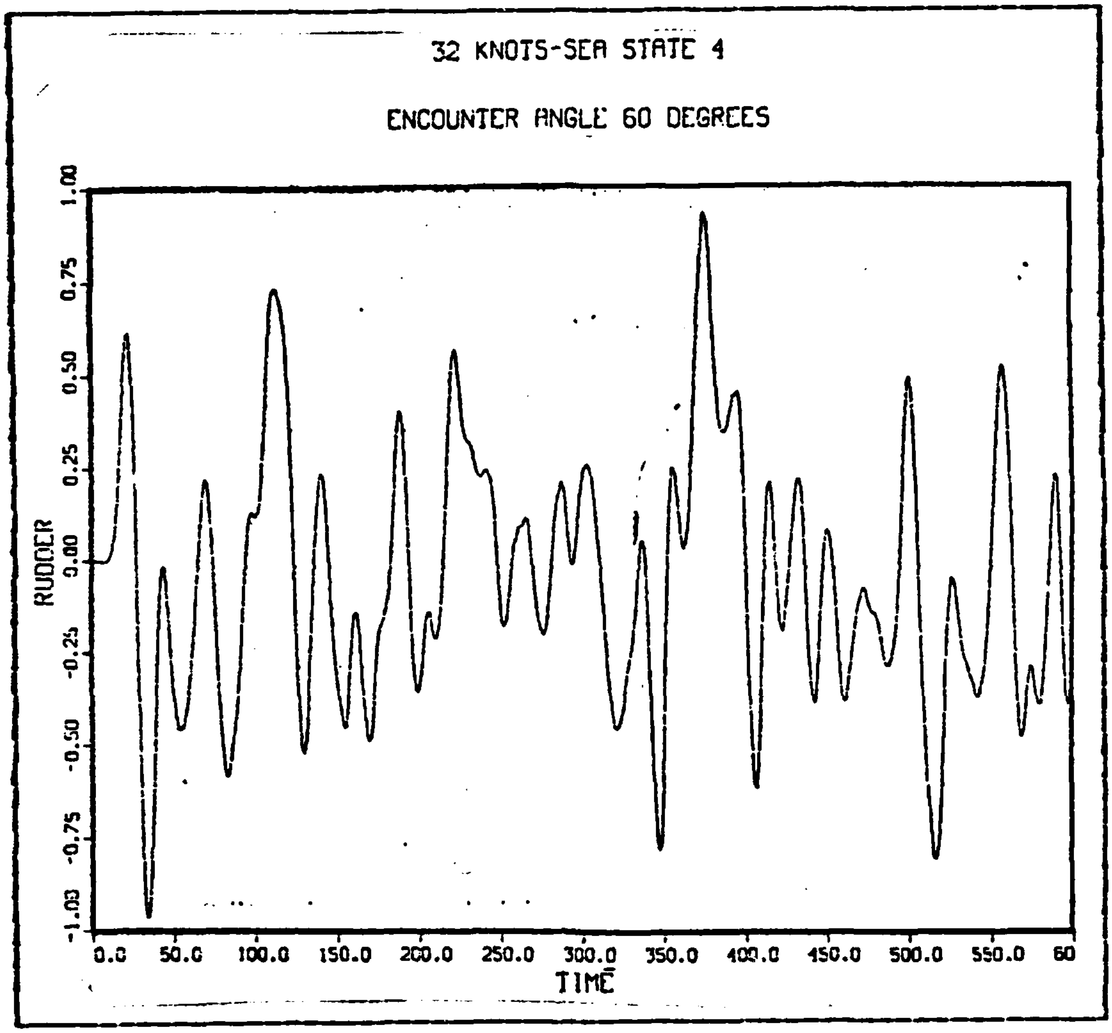

Figure 6.8 RUDDER vs. TIME 60 DEGREES

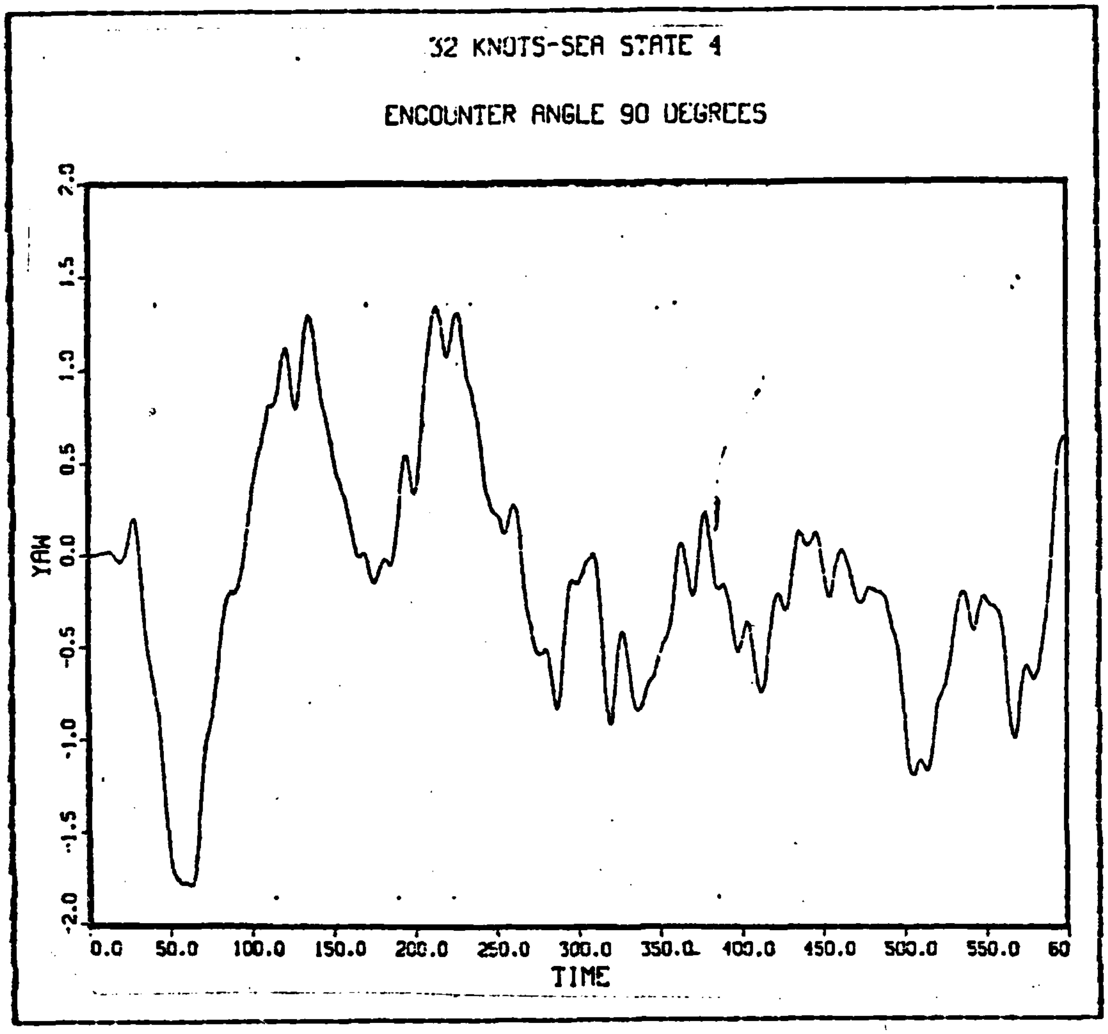

Figure 6.9 YAW vs. TIME 90 DEGREES

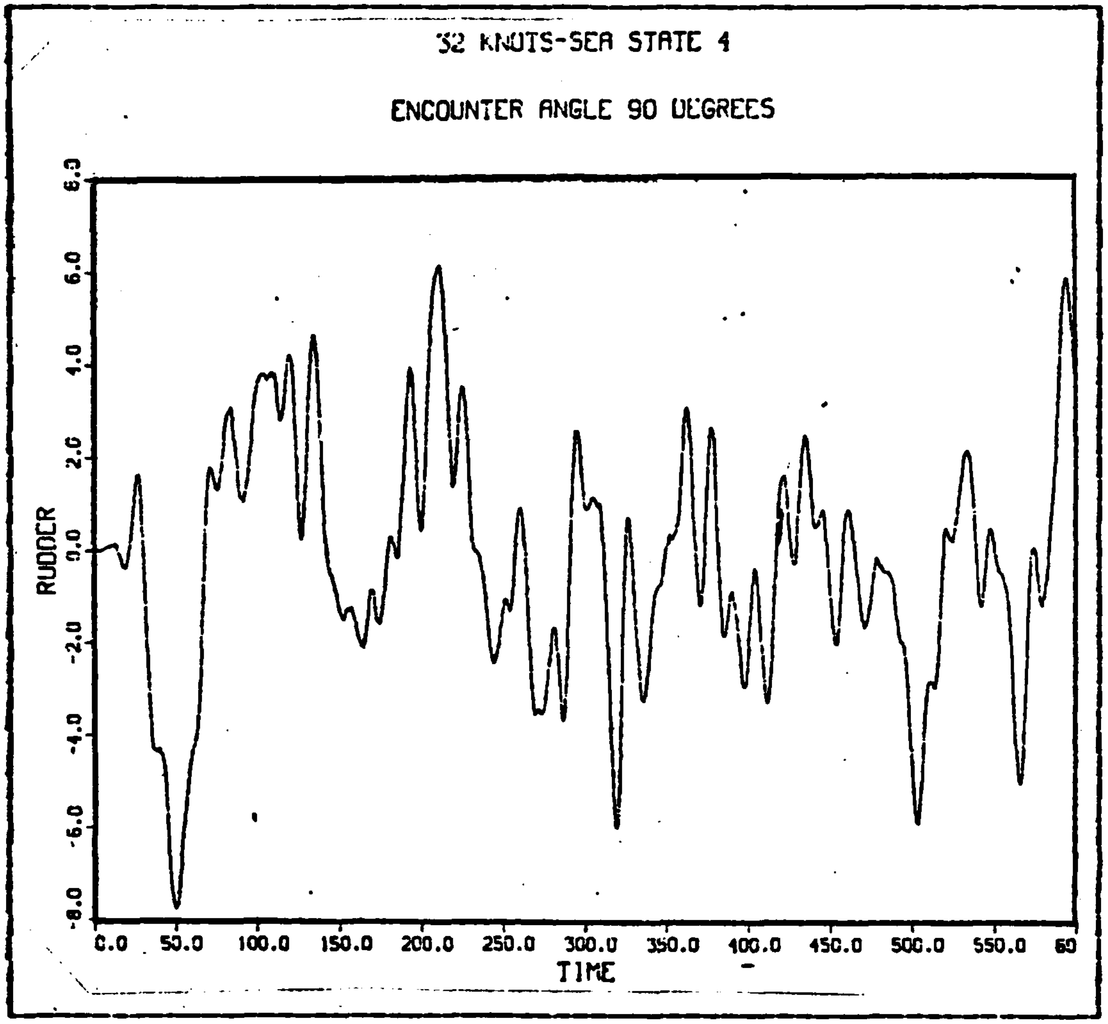

Figure 6.10 RUDDER vs. TIME 90 DEGREES

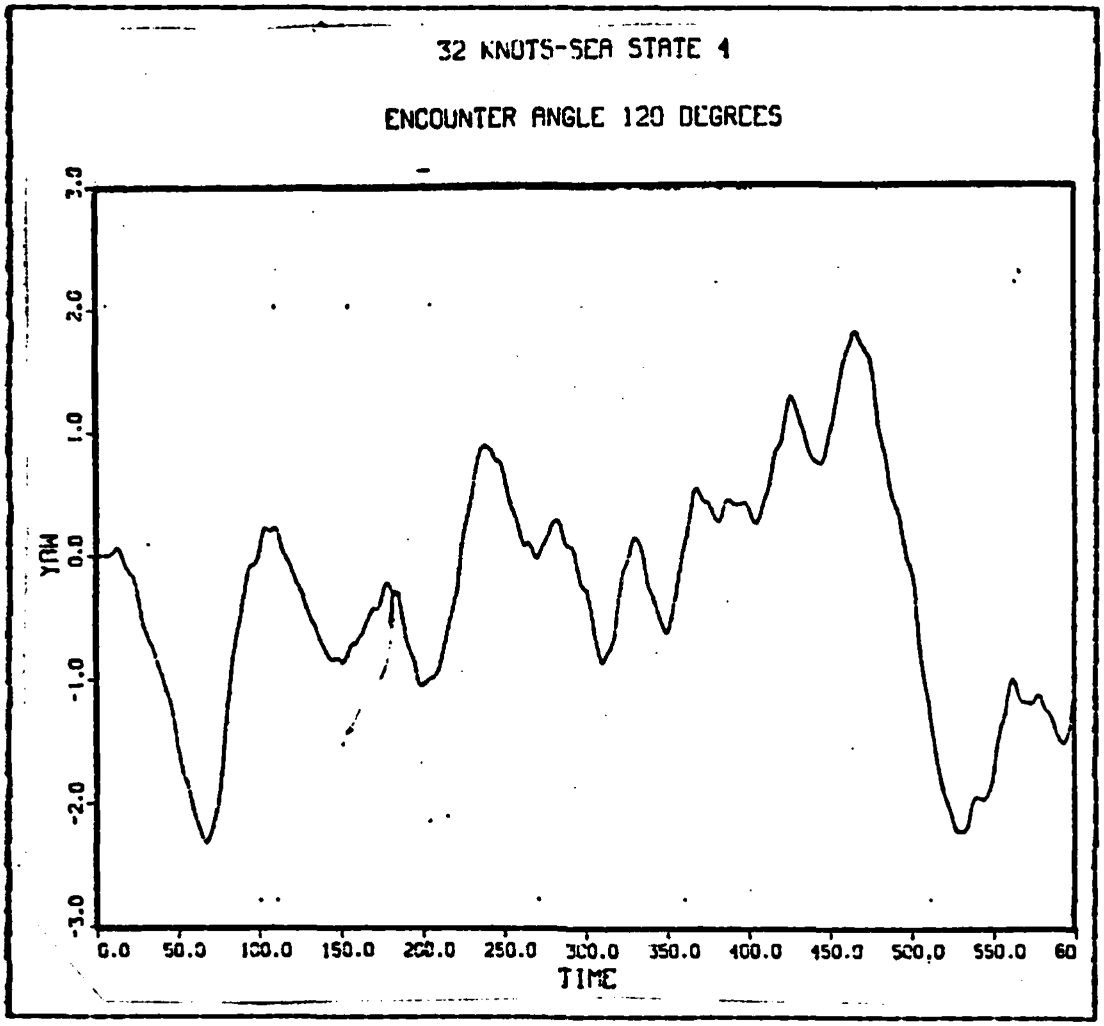

Figure 6.11 YAW vs. TIME 120 DEGREES

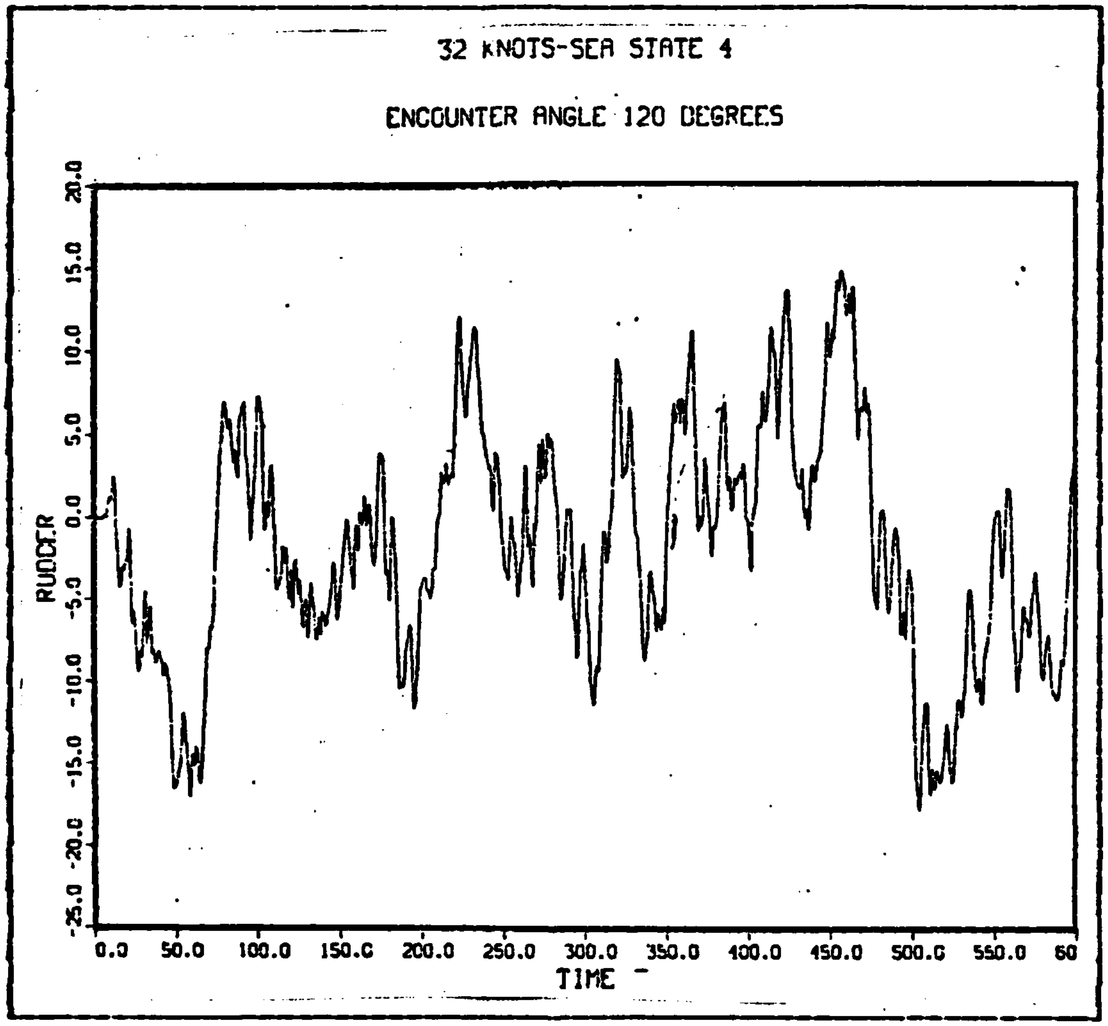

Figure 6.12 RUDDER vs. TIME 120 DEGREES

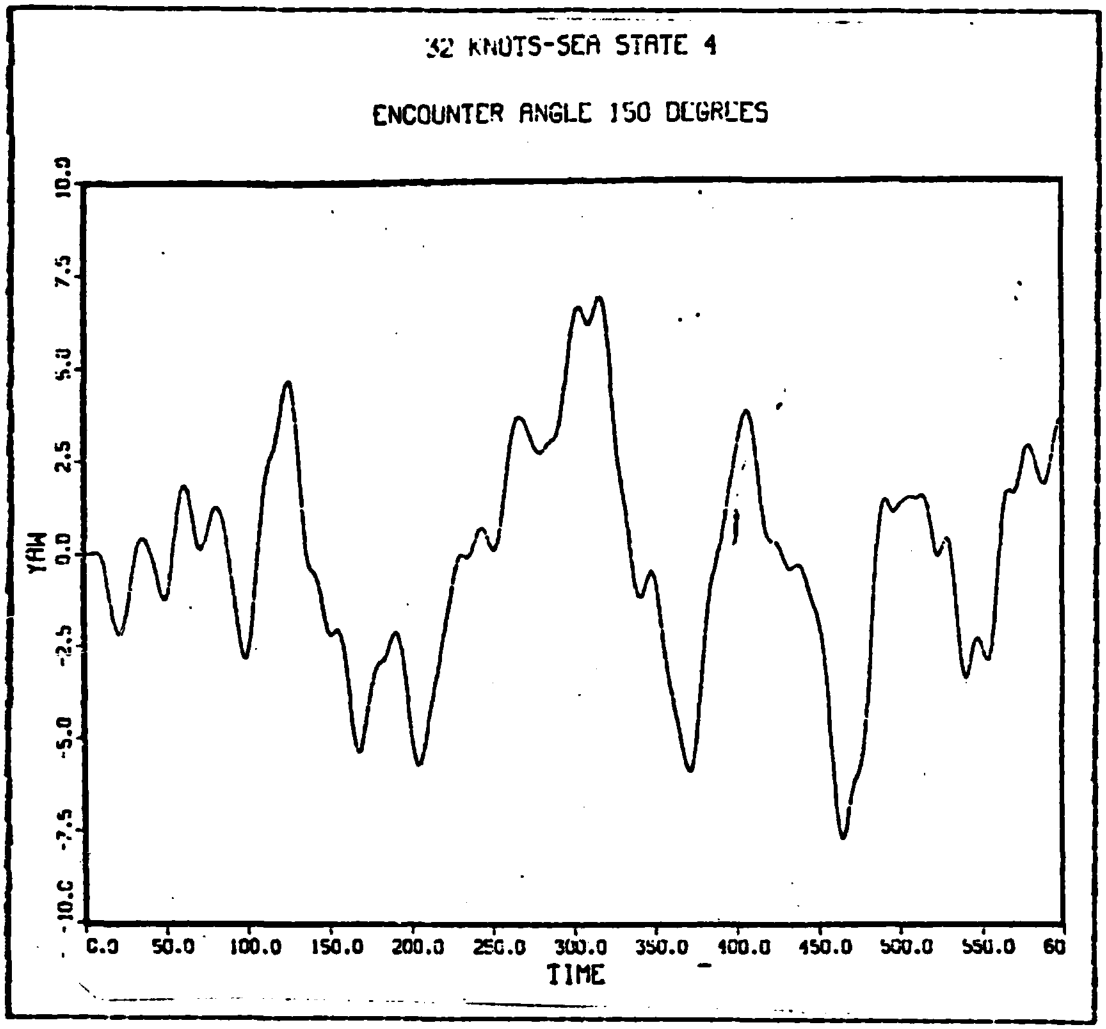

Figure 6.13 YAW vs. TIME 150 DEGREES

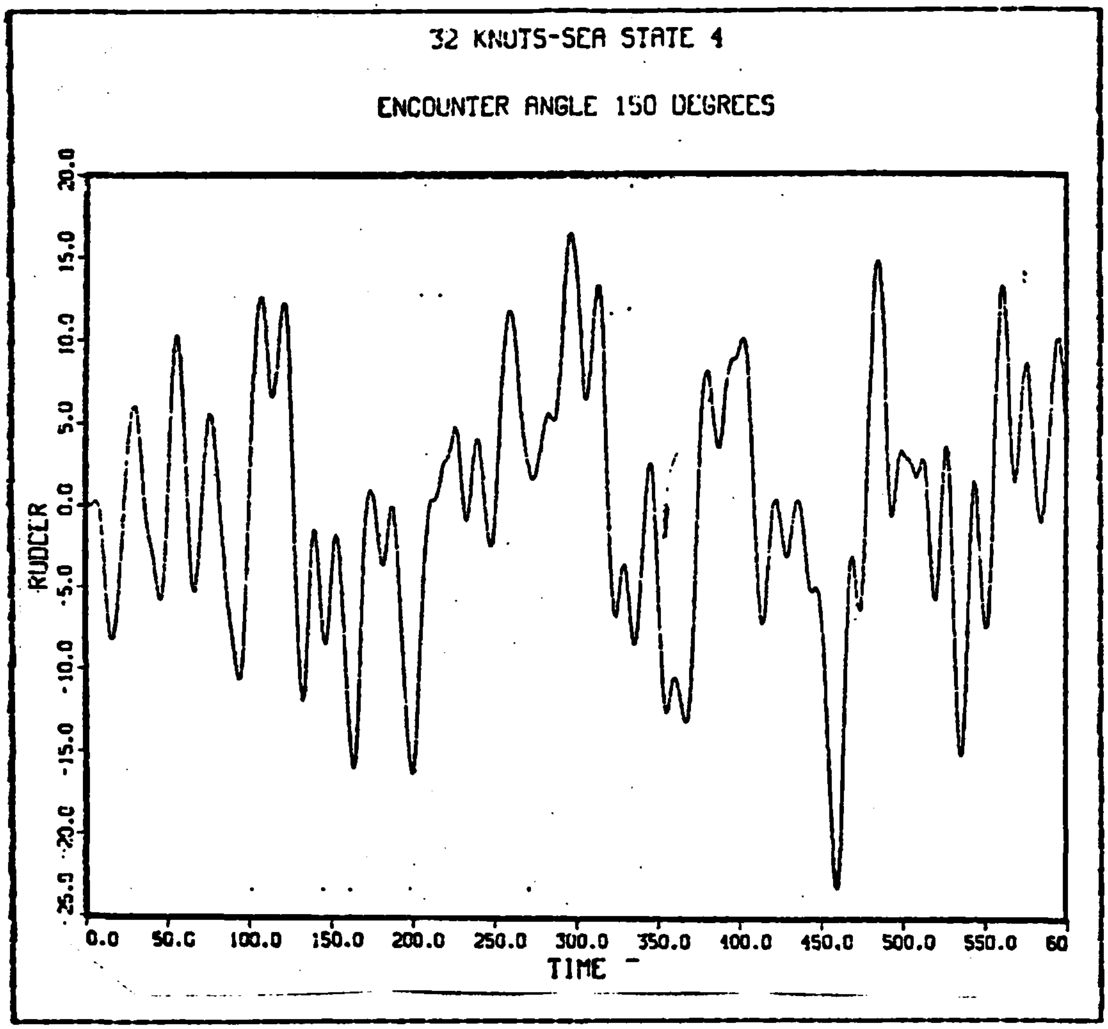

Figure 6.14 RUDDER vs. TIME 150 DEGREES

VII. AN ADAPTIVE CONTROLLER

In a seaway, the controller gains changed dramatically for changes in sea state and encounter angle. An adaptive controller must be used to provide continuous operation on a minimum of the cost function. This Chapter addresses a theoretical design of an adaptive controller.

In the future, there will be better measurement of navigation than can be provided by conventional equipment on board a ship. Presently the Navy is involved in a program that will provide precision navigation data. The NAVSTAR/GLOBAL POSITION SYSTEM (GPS) [Ref. 15] [Ref. 16] [Ref. 17] will provide extremely accurate three-dimensional position and velocity information to users anywhere in the world. The position determinations are based on the measurement of the transit time of RF signals from four satellites of a total constellation of eighteen. This system is scheduled to be fully operational in 1988. At present (1984) there are four NAVSTAR/GPS satellites in operation which allows three to four hours per day of navigation time. Already the Texas Instrument Company markets a receiver for this system where GPS can be used.

The Navy Remote Ocean Sensing System (NROSS) [Ref. 18] will be able to determine wind velocities over the world's oceans with an accuracy sufficient to determine ocean surface waves. It's objective will be to acquire global ocean data for operation and research use by both the military and civil sectors. This system is scheduled to launch its first satellite in June 1989.

The scheme for an adaptive controller is shown in Figure 7.1. Having stored the optimal controller parameters in a look up table as functions of ship speed, sea state, and

encounter angle, the ship operating condition must be known so that the table is useful. NAVSTAR/GPS would identify ship speed and NROSS would identify sea state and encounter angle. The optimal parameters can then be looked up and inserted into the controller. This should place system operation near the minimum J. To ensure fine tuning, a microprocessor programmed, with the function minimization on-line in machine language, with inputs of yaw error and rudder motion of the ship would accomplish the fine tuning rapidly. Since the subroutine is written in Fortran (as used for this study) this would be inappropriate for on-line use.

The adaptive controller can be performed with digital circuits rather than analog components. Garcia [Ref. 19] demonstrates the process for converting an analog controller into a digital controller. Figure 7.2 illustrates the processing of the major components in a digital controller. An analog component circuit can be replaced by an analog to digital converter, a digital processor, and a digital to analog converter. Some of the benefits which can be realized by doing this are:

1. A high-speed processor could actually process a number of multiplexed signals, performing processing functions on a number of independent channels.

2. The processing function is permanent in software, unless deliberately changed, and will not drift with age.

3. The processing function can be changed without changing components, merely by changing software.

4. Accuracy can be made very high and can be changed merely by changing software.

5. Processing, which previously required large components such as inductors in low-frequency controllers, can now be performed by very small digital circuits.

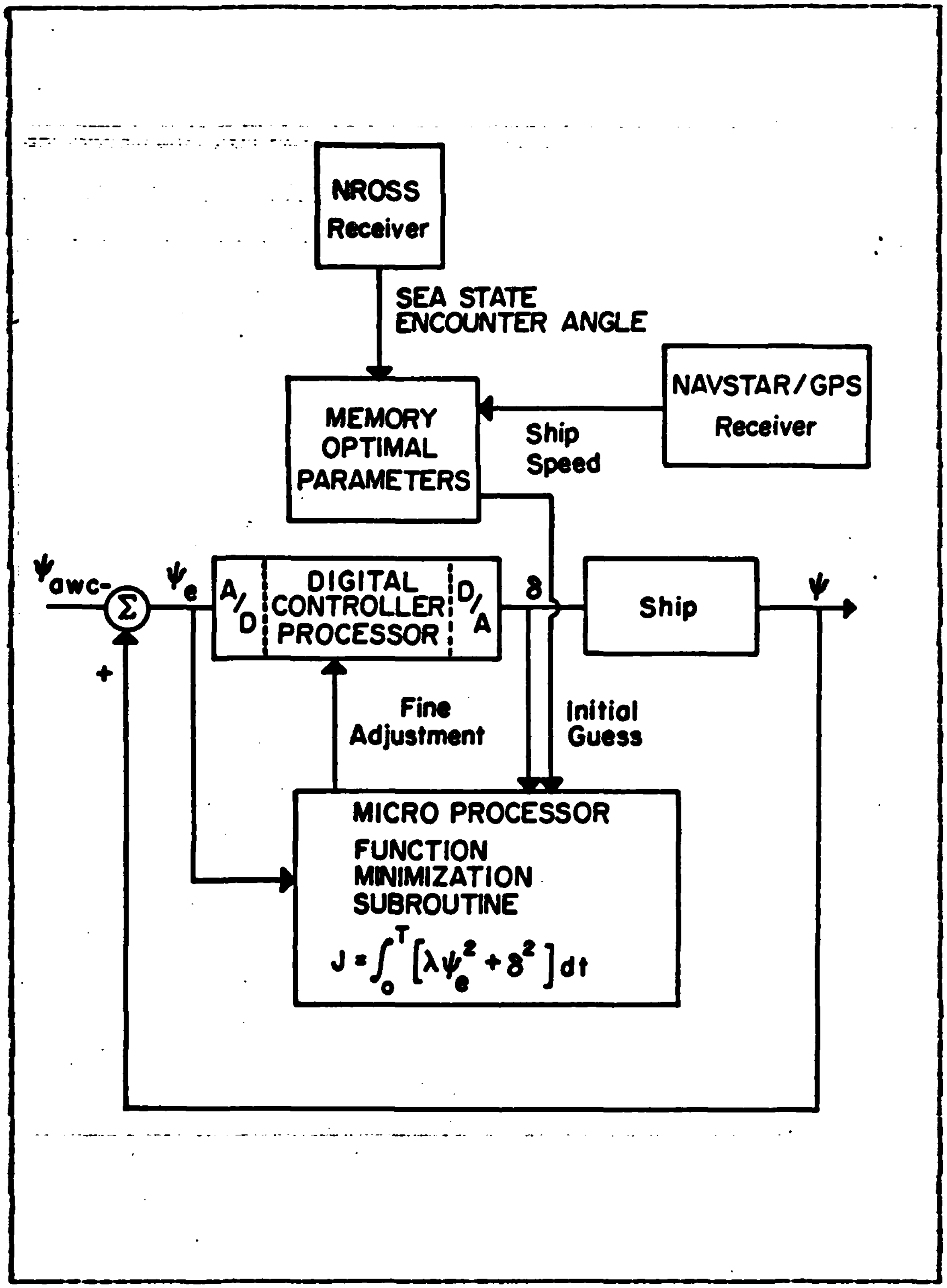

Figure 7.1 ADAPTIVE CONTROLLER

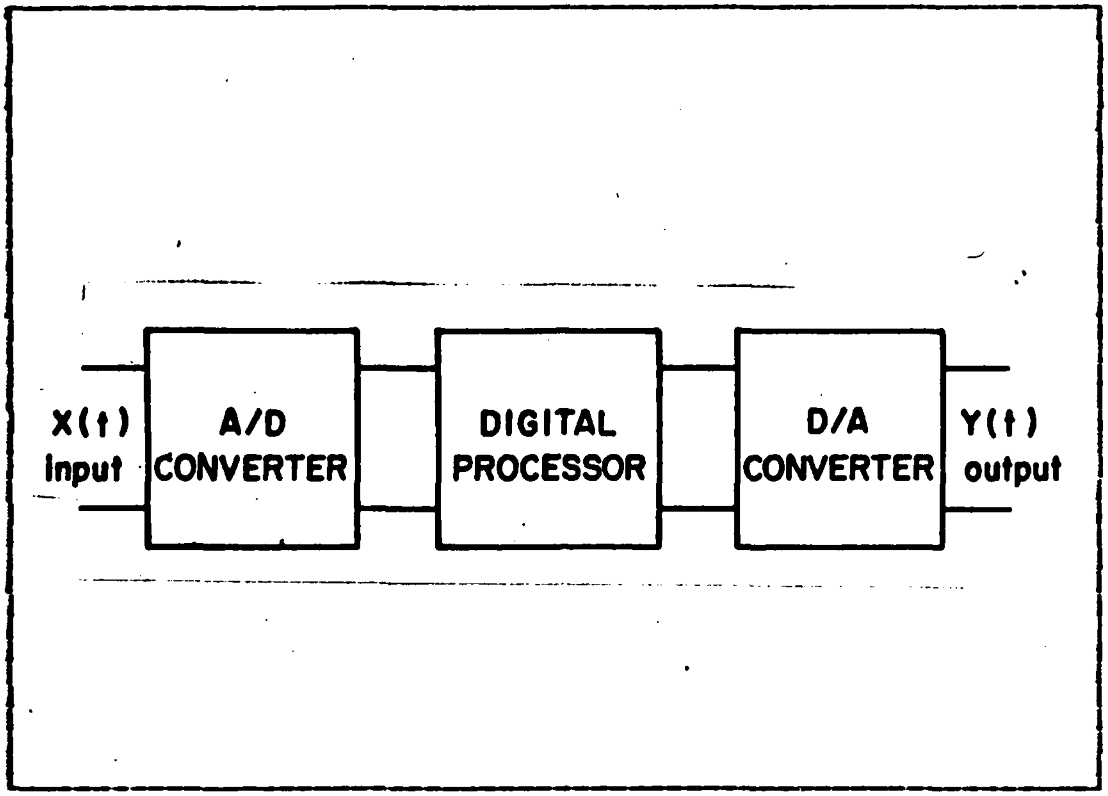

Figure 7.2 DIGITAL BLOCK DIAGRAM

In converting an analog controller to a digital controller, the process can be broken down into the following steps:

1. Determine the desired analog transfer function.
2. Set the sampling frequency.
3. Apply the bilinear z-transformation.
4. Match one point in the s domain to the z domain.
5. Obtain the optimum constant coefficients.
6. Obtain the digital transfer function.
7. Obtain the simulation diagram.

The optimal controller parameters can be stored in memory. Intel company markets a 4 megabit non-volatile read/write bubble memory. It is supported by a VSLI

controller which provides a black box interface. It is easy to use and can be used with any 8- or 16-bit microprocessors. The bubble memory advantage is:

1. Fast access time compared with disk or tape.
2. Non-volatile.
3. Wide temperature range of operation.
4. Working storage.
5. Portable operation
6. Low power.
7. High reliability.

VIII. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

A. CONCLUSIONS

In designing the controller, three different ship models were used. Using the second-order Nomoto model Equation 2.1 allowed comparison of results with Reid's [Ref. 7] [Ref. 10] work. It is clear that the answers obtained by function minimization agree closely with Reid's results as shown in Tables 4 and 5. A better description of the ship is the third-order Nomoto model which involves both the sway and yaw equations. This model includes the two dominating poles of the ship. The best model to describe the dynamics of the ship is a Taylor's series expansion. This allowes both linear and nonlinear terms in the equations of motion to affect the design of the controller.

To determine which controller structure would provide the minimum cost due to steering, various structures were studied. It was found that the dynamics of the plant determines the optimum structure for the controller. In calm water study, when using a second-order Nomoto model, the best structure was controller A. When the third-order Nomoto model Equation 2.2 was used the best structure was controller C, but the difference is slight. Observe that in each case the controller zeros cancel the plant poles. When the equations of motion were used for the plant, the best structure was controller C. When the equations of motion were coupled to a sea state generator and the cost function was minimized in the presence of a seaway, the best structure was controller A. This study concludes that controller A should be used.

A function minimization subroutine is an engineer's tool which can be used in many engineering problems. Previously a

matched filter was designed for the Naval Postgraduate School research project on the Space Transportation System (STS) for the Get Away Special Program. It was matched to the signature of the auxillary power unit (APU) on board the space shuttle. The goal was to turn on the solid state recording system before lift off, to record the acoustic power generated inside the shuttle bay. Basically the matched filter is a Finite Impulse Response (FIR) filter with the weights calculated to obtain the least squared error of the desired output when the input is the signature of the APU. Figure 8.1 shows the scheme used to evaluate the FIR weights.

B. RECOMMENDATIONS FOR FUTURE STUDY

In the future most ships both military and commercial will have GPS receivers as part of their navigation equipment. Using extremely accurate three-dimensional position and velocity information from satellite platforms will allow ships to navigate accurately in and out of ports. The function minimization subroutine is a powerful tool for designing the controller. This routine simply takes the inputs that require minimization and adjusts the parameters to accomplish this task. The cost function for the added drag due to steering is a function of yaw error and rudder motion. The use of function minimization and NAVSTAR/GPS provides the means for optimization for guidance and controll. There are several areas that need future study and work.

1. Should the objective change to track following then it is necessary to minimize the yaw error only. This would be very important both militarily and commercially should a port be mined. If the ship could follow a stringent route, knowledge of mine locations would allow access.

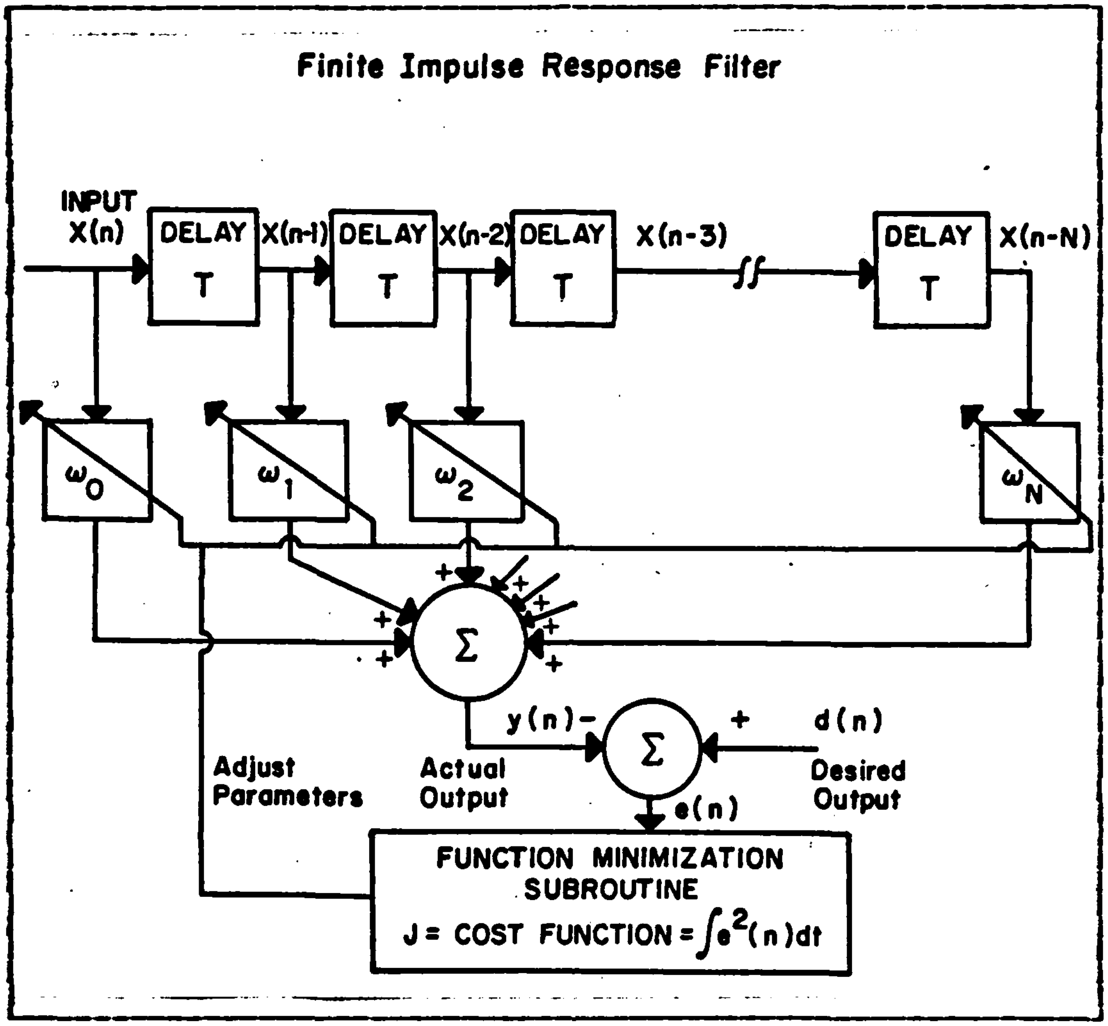

Figure 8.1 MATCHED FILTER DESIGN

2. A controller for orbit keeping for satellites with High-Energy Laser weapons would be very important. The small far-field spot size of a focused laser beam can be selectively focused on the most vulnerable component on the target, Facilitating precision energy deposition, and greatly increasing the probability of a kill.

3. An adaptive controller to minimize track error on board a cruise missile could be programmed for selective targets.

4. Military and commercial aircraft can benefit just as do ships by reducing drag to minimize fuel consumption.

APPENDIX A

PROGRAM TO CALCULATE OPTIMAL GAINS

The program is set up to calculate the optimal gains for controller A. It is referenced in Chapter five and six. It can easily be modified to obtain optimal gains for the rest of the controllers. After obtaining the optimal gains the program most be modified to do a simulation. The program has sufficient comments for appropriate changes. It is referenced in Chapter two.

This program can be modified to obtain the Nomoto models. It is referenced in Chapter two. The following need to be changed.

```
C   GAIN COEFFICIENTS TO BE OPTIMIZED
          K=XX(1)
          TP1=XX(2)
          TZ=XX(3)
          TP2=XX(4)
C   ERROR SIGNAL TO DRIVE RUDDER (YAW ACTUAL - YAW COMMAND)
c   FOR EQUATIONS OF MOTION.
          D=YAW - YAWC
C   ERROR SIGNAL TO DRIVE RUDDER (YAW COMMAND - YAW ACTUAL)
C   FOR NOMOTO 3RD ORDER MODEL.
          D2=YAWC-YAW2
          X1=(D2-X2)/TP1
          X3=K*(TZ*X1+X2)
          X4=(X3-X5)/TP2
C   INTEGRATION
          X2=X2+X1*DELT
          X5=X5+X4*DELT
          YAW2=YAW2+X5*DELT
C   COST FUNCTION
          TDIFF=TDIFF+ (YAW-YAW2)**2
```

PROGRAM TO CALCULATE OPTIMAL GAINS FOR CONTROLLER

```
//GARCIA JOB (2220,0356),'RESEARCH',CLASS=J
// EXEC FRTXCLGP,IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C
C  THIS PROGRAM WILL OBTAIN THE CONTROLLER OPTIMAL GAINS.
C  IT IS REFERENCED IN CHAPTER 5.
C
C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*),AND XL(*).
            DIMENSION XS(3),XU(3),XL(3)
            XS(1)=.427
            XS(2)=48.66
            XS(3)=10.7
C   XS(I) IS THE STARTING GUESS
C   XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C   XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
            XL(1)=.1
            XU(1)=10.
            XL(2)=1.
            XU(2)=200.
            XL(3)=.10
            XU(3)=100.
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
C  IS DISCUSSED IN BOXPLX
        R=9./13.
        NTA=1000
        NPR=100
        NAV=0
        NV=3
        IP=0
C  THE FOLLOWING STATEMENT MUST BE CHANGED TO
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
        CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
        WRITE (6,25)
25      FORMAT(1X,' OPTIMAL GAINS',/)
        DO 30 I=1,3
30      WRITE(6,40)I,XS(I)
40      FORMAT(1X,'X(',I2,')=',F14.7)
        STOP
        END
        SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
       COMMON TDIFF
       REAL*8 L,L2,L3,L4,L5,L6
       REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
       REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
       REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
       REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
       REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
       REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D
       REAL*8 K1,T1,T2,D,X2,DX2,CH(11),S
       DIMENSION XX(3)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
       ETIME=600.
       TIME=0.0
       ICOUNT=1
C  INITIALIZE THE COST FUNCTION
       ISE=0.0
       ISR=0.0
       TDIFF=0.0
       LAMDA=4.2
```

```
C   GAIN COEFFICIENTS TO BE OPTIMIZED
      K1=XX(1)
      T1=XX(2)
      T2=XX(3)
C   X,XDOT,Y,YDOT ARE FIXED COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C   U,UDOT,V,VDOT ARE FIXED COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C   ORDERED SPEED IN  FEET/SEC
C    54.01 FT/SEC=32 KNOTS
      UC=54.01
C   AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C   D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C   SEA DISTURBANCE
C   FORCES IN X,Y DIRECTION COMPUTED IN POUND FORCE
C   MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
C ISEA IS A SWITCH ; ISEA=0 (CALM WATER) ISEA=1 (SEA STATE)
      ISEA=1
C HYDRODYNAMIC COEFFICIENTS ARE INSERTED HERE AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
  200 CONTINUE
      S=DSQRT(U**2+V**2)
C   INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C   ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C   ( COMPENSATOR FILTER )
      YAWE=YAW - YAWC
      DX2=(YAWE-X2)/T2
      D=K1*(T1*DX2+X2)
C   AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C   XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C   DIFFERENT ENCOUNTER ANGLES , SPEED , ENCOUNTER FREQUENCY
C
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C   LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
      YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
```

```
      YVRR=(-0.008) *(.5*RHO*L4/S)
      YVVV=(-0.03) * (.5*RHO*L2/S)
      YRRR=(0.003) * (.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLES, SPEED , ENCOUNTER FREQUENCY
C
C     YVDOT=(-0.0039)*(.5*RHO*L3)
C SPEED=32 KNOTS,ENCOUNTER ANGLE =150 ,ENCOUNTER FREQ =.75
      YVDOT=-2.3043E+C6
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213) *(.5*RHO*L3*S)
      NR=(-0.00105) *(.5*RHO*L4*S)
      ND=(-0.0007) *(.5*RHO*L3*s**2)
      NVVR=(-0.015) *(.5*RHO*L4/S)
      NVRR=(-0.008) *(.5*RHO*L5/S)
      NVVV=(0.01) *(.5*RHO*L3/S)
      NRRR=(-0.006) *(.5*RHO*L6/S)
      NDDD=(0.0001) *(.5*RHO*L3*S**2)
C NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED FOR
C DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
C     NRDOT=(-0.00027)*(.5*RHO*L5)
C  SPEED=32 KNOTS,ENCOUNTER ANGLE =150 ,ENCOUNTER FREQ =.75
      NRDOT=-1.5096E+11
C  SETS SEA STATE TO ZERO
      IF (ISEA.EQ.1) GO TO 30
      FX=0.
      FY=0.
      MZ=0.
      GC TO 35
C  TABLE LOOK UP OF SEA DISTURBANCE,
C  UNIT 12 HAS THE SEA STATE DATA NAMED CH
C  IT MUST BE SYNCHRONIZED BY APPROPRIATELY
C  CALLING CH IN THE PROPER TIME IN THE LOOP.
C  THE SEA DATA WAS CREATED FOR 600 SECONDS
C  WITH AN INCREMENTAL INTERVAL OF 1 SECOND.
 30   READ (12) CH
      FX=CH(3)
      FY=CH(4)
      MZ=CH(8)
 35   CCNTINUE
C  U ACTUAL SPEED
C  UC CCMMANDED SPEEC
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  ECUATICNS OF MOTICN
c  FOR CONSTANT SPEEC COMMENT THE NEXT TWO INSTRUCTIONS
      UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
     1 + XDD*D*D +  FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V +  (YR-MASS*U)*R + YD*D + YVVR*V**2*R
     1 + YVRR*V*R**2 + YVVV*V**3
     2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=( NV*V + NR*R + ND*D + NVVR*V**2*R
     1 + NVRR*V*R**2 + NVVV*V**3
     2 + NRRR*R**3 + NDDD*D**3 + MZ )/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ.11) GO TO 50
      GC TO 300
C  CCNVERT RADIANS TC DEGREES
 50   YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
     YAWC=YAWC*57.296
C     WRITE (6,100) TIME,XP,X,XDOT,Y,YDOT
C    1  ,UC,U,UDOT,V,VDOT,YAWC,YAWDEG,RDEG,RDDEG,DDEG
 100 FORMAT(1X,'TIME=',F8.3,' SEC   XP=',F10.2,' LBF   X='
     1,F8.2,' FT  XDCT=',F8.4,' FT/SEC  Y=',F8.2,
```

```
     2' FT  YDOT=',F8.4,' FT/SEC',/,2X,' UC=',F8.4,
     3' FT/SEC    U=',F8.4,' FT/SEC    UDOT=',F10.6,
     4 ' FT/SEC**2    V=',F8.4,' FT/SEC    VDOT=',F10.6,
     5' FT/SEC**2',/,2X,'YAWC=',F8.4,' DEG   YAW=',F15.7,
     6' DEG    YAW RATE=',F15.7,' DEG/SEC    YAW ACCEL='
     7,F15.7,' DEG/SEC**2',/,2X,'RUDDER =',F15.7,' DEG ',/)
      ICOUNT=1
C  TEST IF WANT TO STOP
 300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.0
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
      XDOT=U*DCOS(YAW)-V*DSIN(YAW)
      YDOT=U*DSIN(YAW)+V*DCOS(YAW)
      X=X+XDOT*DELT
      Y=Y+YDOT*DELT
      TIME=TIME+DELT
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWE**2
      ISR=ISR + D**2
      GO TO 200
C    J= TDIFF = COST FUNCTION
 400  TDIFF=ISE+ISR
      WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2
 500  FORMAT(' ',1X,'ISE=',F15.7,'  ISR=',F15.7,'  TOTAL='
     1,F15.7,2X,'K1=',F15.7,2X,'T1=',F15.7,2X,'T2=',F15.7)
      REWIND 12
      RETURN
      END
C  DELETE ALL THE FOLLOWING SUBROUTINE IF SIMULATION ONLY
C  AND NOT OPTIMIZATION IS WANTED
C
C     .......................................................
C
C     SUBROUTINE BOXPLX                (CATEGORY H0)
C
C     PURPOSE
C
C BOXPLX IS A SUBROUTINE USED TO SOLVE THE PROBLEM OF
C locacting A MINIMUM (OR MAXIMUM) OF AN ARBITRARY OBJECT-
C ive function SUBJECT TO ARBITRARY EXPLICIT AND/OR
C implicit constraints by tHE COMPLEX METHOD OF M.J. BOX.
C explicit constraints are dEFINED AS UPPER AND LOWER
C bounds on the independent variables IMPLICIT constraints
C may be arbitrary function of the varIABLES.  TWO FUN-
C ction subprogram to evaluate the objective FUNCTION AND
C implicit conSTRAINTS, RESPECTIVELY, must be SUPPLIED
C by the user (see EXAMPLE BELOW). BOXPLX ALSO HAS tHE
C option to perform integer programming, where the values
C of the independent variables are restricted to integers.
C
C     USAGE
C
C        CALL BOXPLX (NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
C
C
C     DESCRIPTION OF PARAMETERS
C
C NV   AN INTEGER INPUT DEFINING THE NUMBER OF INDEPENDENT
C      VARIABLES OF THE OBJECTIVE FUNCTION TO BE MINIMIZED.
C   NOTE:  MAXIMUM NV + NAV IS PRESENTLY 50.  MAXIMIM NV IS
C     25.  IF THESE LIMITS MUST BE EXCEEDED, PUNCH A SOURCE
C        DECK IN THE USUAL MANNER, AND CHANGE THE DIMENSION
C        STATEMENTS.
```

```
C
C NAV AN INTEGER INPUT DEFINING THE NUMBER OF AUXILIARY var
C iaBLES THE USER WISHES TO DEFINE FOR HIS OWN CONVENIENCE.
C TYPICALLY HE MAY WISH TO DEFINE THE VALUE OF EACH IMPLICI
C CONSTRAINT FUNCTION AS AN AUXILIARY VARIABLE.  IF THIS
C IS DONE, THE OPTIONAL OUTPUT FEATURE OF BOXPLX CAN BE
C USED TO OBSERVE THE VALUES OF THOSE CONSTRAINTS AS THE
C SOLUTION PROGRESSES.  AUXILIARY VARIABLES, IF USED,
C SHOULD BE EVALUATED IN FUNCTION KE (DEFINED BELOW).
C NAV MAY BE ZERO.
C
C NPR  INPUT INTEGER CONTROLLING THE FREQUENCY OF OUTPUT
c desired for diagnostic purposes.
C IF NPR .LE. 0, NO OUTPUT WILL BE
C PRODUCED BY BOXPLX.  OTHERWISE, THE CURRENT COMPLEX OF
C K= 2*NV VERTICES AND THEIR CENTROID WILL BE OUTPUT AFTER
C EACH NPR PERMISSIBLE TRIALS.  THE NUMBER OF TOTAL TRIALS,
C NUMBER OF FEASIBLE TRIALS, NUMBER OF FUNCTION EVALUATIONS
C AND NUMBER OF IMPLICIT CONSTRAINT EVALUATIONS ARE IN-
C CLUDED IN THE OUTPUT.
C ADDITIONALLY, (WHEN NPR .GT. 0) THE SAME INFORMATION
C WILL BE OUTPUT:
C
C 1) IF THE INITIAL POINT IS NOT FEASIBLE,
C 2) AFTER THE FIRST COMPLETE COMPLEX IS GENERATED,
C 3) IF A FEASIBLE VERTEX CANNOT BE FOUND AT SOME TRIAL,
C 4) IF THE OBJECTIVE VALUE OF A VERTEX CANNOT BE MADE
C    NO-LONGER-WORST.
C 5) IF THE LIMIT ON TRIALS (NTA) IS REACHED AND,
C 6) WHEN THE OBJECTIVE FUNCTION HAS BEEN UNCHANGED FOR
c 2*NV TRIALS, INDICATING A LOCAL MINIMUM HAS BEEN
C FOUND.
C
C IF THE USER WISHES TO TRACE THE PROGRESS OF A SOLUTION,
C A CHOICE OF NPR = 25, 50 OR 100 IS RECOMMENDED.
C
C NTA  INTEGER INPUT OF LIMIT ON THE NUMBER OF TRIALS
c allowed in the calculation.
C IF THE USER INPUTS NTA .LE. 0, A default
C VALUE OF 2000 IS USED.  WHEN THIS LIMIT IS REACHED
c CONTROL RETURNS TO THE CALLING PROGRAM WITH THE BEST
C ATTAINED OBJECTIVE FUNCTION VALUE IN YMN, AND THE BEST
C ATTAINED SOLUTION POINT IN XS.
C
C R   A REAL NUMBER INPUT TO DEFINE THE FIRST RANDOM NUMBER
C USED IN DEVELOPING THE INITIAL COMPLEX OF 2*NV VERTICIES.
C (0. .GT. R .LT. 1.) IF R IS NOT WITHIN THESE BOUNDS,
C IT WILL BE REPLACED BY 1./3. .
C
C XS   INPUT REAL ARRAY DIMENSIONED AT LEAST NV+NAV.
c the first nv must contain a
C FEASIBLE ORIGIN FOR STARTING THE CAL-
C CULATION.  THE LAST NAV NEED NOT BE INITIALIZED.  UPON
C RETURN FROM BOXPLX, THE FIRST NV ELEMENTS OF THE ARRAY
C CONTAIN THE COORDINATES OF THE MINIMUM OBJECTIVE
C function, AND THE REMAINING NAV (NAV .GE. 0) CONTAIN THe
C values of THE CORRESPONDING AUXILIARY VARIABLES.
C
C IP   INTEGER INPUT FOR OPTIONAL INTEGER PROGRAMMING.
C if ip=1, THE VALUES OF THE INDEPENDENT VARIABLES WILL
C be replaced WITH INTEGER VALUES (STILL STORED AS REAL*4).
C
C XU   A REAL ARRAY DIMENSIONED AT LEAST NV INPUTTING THE
C upper BOUND ON EACH INDEPENDENT VARIABLE, (EACH EXPLICIT
C cONSTRAINT). INPUT VALUES ARE SLIGHTLY ALTERED BY BOXPLX.
C
C XL   A REAL ARRAY DIMENSIONED AT LEAST NV INPUTTING THE
c lower bound on each independent
C VARIABLE, (EACH EXPLICIT CONstraint).
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C NOTE:  FOR BOTH XU AND XL CHOOSE REASONABLE
C VALUES IF NONE ARE GIVEN, NOT VALUES WHICH ARE
C magnitudes ABOVE OR BELOW THE EXPECTED SOLUTION.
C input values are SLIGHTLY ALTERED BY BOXPLX.
C
C YMN  THIS OUTPUT IS THE VALUE (REAL*4) OF THE OBJECTIVE
C funcTION,CORRESPONDING TO THE SOLUTION POINT OUTPUT IN XS
C
C IER  INTEGER ERROR RETURN.  TO BE INTERROGATED UPON
C return FROM BOXPLX.  IER WILL BE ONE OF THE FOLLOWING:
C
C =-1  CANNOT FIND FEASIBLE VERTEX OR FEASIBLE CENTROID
C AT THE START OR A RESTART (SEE 'METHOD' BELOW).
C =0   FUNCTION VALUE UNCHANGED FOR 'N' TRIALS.   (WHERE
C N=6*NV+10)  THIS IS THE NORMAL RETURN PARAMETER.
C =1   CANNOT DEVELOP FEASIBLE VERTEX.
C =2   CANNOT DEVELOP A NO-LONGER-WORST VERTEX.
C =3   LIMIT ON TRIALS REACHED.   (NTA EXCEEDED)
C NOTE:  VALID RESULTS MAY BE RETURNED IN ANY OF THE
C        ABOVE CASES.
C
C  EXAMPLE OF USAGE
C
C THIS EXAMPLE MINIMIZES THE OBJECTIVE FUNCTION SHOWN IN
C the EXTERNAL FUNCTION FE(X).  THERE ARE TWO INDEPENDENT
C variABLES X(1) & X(2), AND TWO IMPLICIT CONSTRAINT
C function X(3) & X(4) WHICH ARE EVALUATED AS AUXILIARY
C variables (see EXTERNAL FUNCTION KE(X) ).
C
C DIMENSION  XS(4),XU(2),XL(2)
CC
CC   STARTING GUESS
C       XS(1) = 1.0
C       XS(2) = 0.5
CC   UPPER LIMITS
C       XU(1) = 6.0
c       XU(2) = 6.0
CC   LOWER LIMITS
C       XL(1) = 0.0
C       XL(2) = 0.0
CC
C       R = 9./13.
C       NTA = 5000
C       NPR = 50
C       NAV = 2
C       NV = 2
C       IP = 0
CC
C       CALL BOXPLX (NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
C       WRITE(6,1)  ((XS(I),I=1,4),YMN,IER)
C     1FORMAT (////,'    THE POINT IS LOCATED AT (XS(I)=) '
c     2,4(e13.7,5x),///,
C     3'    AND THE FUNCTION VALUE IS ',E13.7,' IER = ',I5)
CC
C       STOP
C       END
CC
CC
C       FUNCTION  KE(X)
C EVALUATE CONSTRAINTS.  SET KE=0 IF NO IMPLICIT CONSTRAINT
C is viOLATED, OR SET KE=1 IF ANY IMPLICIT
c constraint is violated.
C       DIMENSION X(4)
C       X1 = X(1)
C       X2 = X(2)
C       KE = 0
C       X(3) = X1 + 1.732051*X2
C       IF (X(3) .LT. 0. .OR. X(3) .GT. 6.) GO TO 1
C       X(4) = X1/1.732051 -X2
```

```
C      IF (X(4) .GE. C.)  RETURN
CC
C    1 KE = 1
C      RETURN
C      END
CC
CC
C      FUNCTION  FE(X)
C      DIMENSION X(4)
CC
CC   THIS IS THE OBJECTIVE FUNCTION.
C      FE= -(X(2)**3 *(9.-(X(1)-3.)**2)/(46.76538))
C      RETURN
C      END
C
C      METHOD
C
C  THE COMPLEX METHOD IS AN EXTENSION AND ADAPTION OF
c  the simple method of linear programming.
C  STARTING WITH ANY ONE feasible point in n-dimension
C  A "COMPLEX" OF 2*N vertices is constructed by
C  SELECTING RANDOM POINTS WITHIN THE feasible
C  REGION.  FOR THIS PURPOSE N COORDINATES ARE FIRST
C  RANDOMLY CHOSEN WITHIN THE SPACE BOUNDED BY EXPLICIT CON-
C  STRAINTS.  THIS DEFINES A TRIAL INITIAL VERTEX.
c  it is then checked for possible violation
C  OF IMPLICIT CONSTRAINTS.  IF one or more are violated,
C  THE TRIAL INITIAL VERTEX IS DISPLACED half of its
C  DISTANCE FROM THE CENTROID OF PREVIOUSLY SELECTED initial
C  VERTICES.  IF NECESSARY THIS DISPLACEMENT PROCESS IS
C  REPEATED UNTIL THE VERTEX HAS BECOME FEASIBLE.  IF THIS
C  FAIL  TO happen after 5*n+10 displacements,
C  THE SOLUTION IS ABANDONED. AFTER EACH VERTEX IS ADDED
C  TO THE COMPLEX, THE CURRENT centroid is checked for
C  FEASIBILITY.  IF IT IS INFEASIBLE, the last trail
C  VERTEX IS ABANDONED AND AN EFFORT TO GENERATE an alter-
C  ATIVE TRIAL VERTEX IS MADE.  IF 5*N+10 VERTICES ARE
C  ABANDONED CONSECUTIVELY, THE SOLUTION IS TERMINATED.
C
C  IF AN INITIAL COMPLEX IS ESTABLISHED, THE BASIC
c  computation loop is initiated.
C  THESE INSTRUCTIONS FIND THE CURRENT WORST vertex, that
C  IS, THE VERTEX WITH THE LARGEST CORRESPONDING value for
C  THE OBJECTIVE FUNCTION, AND REPLACE THAT VERTEX BY
C  ITS OVER-REFLECTION THROUGH THE CENTROID OF ALL OTHER
c  vertices. (if the vertex to be
C  REPLACED IS CONSIDERED AS A VECTOR IN n-space,
C  ITS OVER-REFLECTION IS OPPOSITE IN DIRECTION, IN-
C  CREASED IN LENGTH BY THE FACTOR 1.3, AND COLLINEAR WITH
C  THE REPLACED VERTEX AND CENTROID OF ALL OTHER VERTICES.)
C
C  WHEN AN OVER-REFLECTION IS NOT FEASIBLE OR REMAINS
c  WORST, IT IS CONSIDERED NOT-PERMISSIBLE
C  AND IS DISPLACED HALFWAY TOWARD THE CENTROID.
C  AFTER FOUR SUCH ATTEMPTS ARE MADE UNSUCCESSFULLY
C  EVERY FIFTH ATTEMPT IS MADE BY REFLECTING THE OFFENDING
c  VERTEX THROUGH THE PRESENT BEST
C  VERTEX, INSTEAD OF THROUGH THE CENTROID. IF 5*n+10
C  DISPLACEMENTS AND OVER-REFLECTIONS OCCUR WITHOUT A
C  SUCCESSFUL (PERMISSIBLE) RESULT, THE CURRENT BEST
C  VERTEX IS TAKEN AS AN INITIAL FEASIBLE POINT FOR A
c  RESTART RUN OF THE COMPLETE PROCESS.
C  RESTARTING IS ALSO UNDERTAKEN WHEN 6*nv+10 CONSECUTIVE
C  TRIALS HAVE BEEN MADE WITH NO SIGNIFICANT CHANGE IN THE
C  VALUE OF THE OBJECTIVE FUNCTION.  IN ALL CASES,
C  RESTARTING IS INHIBITED IF THE LAST RESTART DID NOT
C  PRODUCE A SIGNIFICANT IMPROVEMENT IN THE MINIMUM
c  ATTAINED.
C
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```
C IT IS RECOMMENDED THAT THE USER READ THE REFERENCE FOR
C FURTHER USEFUL INFORMATION.  IT SHOULD BE NOTED THAT THE
C ALGORITHM DEFINED THERE HAS BEEN ALTERED TO FIND THE
C CONSTRAINED MINIMUM, RATHER THAN THE MAXIMUM.
C
C
C
C      REMARKS
C
C THE INTEGER PROGRAMMING OPTION WAS ADDED TO THIS PROGRAM
C AS SUGGESTED IN REFERENCE (2).  A MIXED
c integer/continuous variable version of boxplx
C WOULD BE EASY TO CREATE BY DEclaring "ip" to be an array
C OF NV CONTROL VARIABLES WHERE IP (i)=1 would indicate
C THAT THE I-TH VARIABLE IS TO BE CONFINED to integer
C VALUES.  EACH STATEMENT OF THE FORM 'IF (IP .EQ. 1)' etc.
C WOULD THEN NEED TO BE ALTERED TO 'IF (IP(I) .EQ. 1)' etc.
C , WHERE THE SUBSCRIPT IS APPROPRIATELY CHOSEN.  NORMALLY,
C XU AND XL VALUES ARE ALTERED TO BE AN EPSILON 'WITHIN'
c actual values
C DECLARED BY THE USER.  THIS ADJUSTMENT IS NOT MADE
C WHEN IP=1.
C
C NOTE:  NO NON-LINEAR PROGRAMMING ALGORITHM CAN GUARANTEE
c that the answer found is the global
C MINIMUM, RATHER THAN JUST A local minimum. however,
C ACCORDING TO REF.2, THE COMPLEX method has an advantage
C IN THAT IT TENDS TO FIND THE GLOBAL minimum more
C FREQUENTLY THAN MANY OTHER NON-LINEAR PROGRAM-
C MING ALGORITHMS.
C
C IT SHOULD BE NOTED THAT THE AUXILIARY VARIABLE FEATURE
c CAN ALSO BE USED TO DEAL WITH
C PROBLEMS CONTAINING EQUALITY CONstraints. any equality
C CONSTRAINT IMPLIES THAT A GIVEN VARiable is not truly
C INDEPENDENT.  THEREFORE, IN GENERAL, ONE variable
C INVOLVED IN AN EQUALITY CONSTRAINT CAN BE RENUMBERED from
C THE SET OF NV INDEPENDENT VARIABLES AND ADDED TO THE SET
C OF NAV AUXILIARY VARIABLES.  THIS USUALLY INVOLVES
C renumbering THE INDEPENDENT VARIABLES OF THE GIVEN
C problem
C SUBROUTINES AND FUNCTIONS REQUIRED
C
C SUBROUTINE 'BOUT' AND FUNCTION 'FBV' ARE INTEGRAL
C parts of THE BOXPLX PACKAGE.
C
C TWO FUNCTIONS MUST BE SUPPLIED BY THE USER.  THE FIRST,
c ke(x), is used to evaluate the implicit
C CONSTRAINTS.  SET KE=0 AT THE beginning of the function
C , THEN EVALUATE THE IMPLICIT CONstraints. in the example
C ABOVE, THE FIRST CONSTRAINT, X(3), must be within the
C RANGE (0. .LE. X(3) .LE. 6.).  THE SECOND constraint x(4)
C , MUST BE .GE. 0. .  IF EITHER CONSTRAINT IS not within
C THESE BOUNDS, CONTROL IS TRANSFERRED TO STATEMENT 1,
C AND KE IS SET TO "1" AND CONTROL IS RETURNED TO BOXPIX.
C
C THE SECOND FUNCTION THE USER MUST PROVIDE EVALUATES THE
c objective function. it is
C CALLED FE(X) AS SHOWN IN THE EXAMple above, and fe
C MUST BE SET TO THE VALUE OF THE OBJECTIVE function
C CORRESPONDING TO CURRENT VALUES OF THE NV INDEPENDENT
C VARIABLES IN ARRAY 'X'.
C
C      REFERENCES
C
C BOX, M. J., "A NEW METHOD OF CONSTRAINED OPTIMIZATION
C and a COMPARISON WITH OTHER METHODS",
C computer journal, 8 apr. '65, PP. 45-52.
C
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C BEVERIDGE G., AND SCHECHTER R., "OPTIMIZATION: THEORY AND
C PRACTICE", MCGRAW-HILL, 1970.
C
C     PROGRAMMER
C
C        R.R. HILLEARY 1/1966.
C        REVISED FOR SYSTEM 360 4/1967
C        CORRECTED  1/1969
C        REVISED/EXTENDED BY L.NOLAN/R.HILLEARY  2/1975
C        CORRECTED  8/1976
C
C
C     ..................................................
C
C
      SUBROUTINE BOXPLX (NV,NAV,NPR,NTZ,RZ,XS,IP,BU,BL,YMN,IER)
C
      DIMENSION V(50,50), FUN(50), SUM(25), CEN(25), XS(NV)
     1,bu(nv),bl(NV)
C
      KV = 5
      EP = 1.E-6
      NTA = 2000
      IF (NTZ.GT.0) NTA = NTZ
      R = RZ
      IF (R.LE.0..OR.R.GE.1.) R=1./3.
      NVT = NV+NAV
C
C            TOTAL VARS, EXPLICIT PLUS IMPLICIT
      NT = 0
C            CURRENT TRIAL NO.
      NPT = 0
C            CURRENT NO. OF PERMISSIBLE TRIALS
      NTFS = 0
C        CURRENT NO. OF TIMES F HAS BEEN ALMOST UNCHANGED
C
C               CHECK FEASIBILITY OF START POINT
C
      DO 4 I=1,NV
      VT = XS(I)
      IF (BL(I).LE.VT) GO TO 1
      II = -I
      VT = BL(I)
      GO TO 2
    1 IF (BU(I).GE.VT) GO TO 3
      II = I
      VT = BU(I)
    2 IF (NPR.GT.0) WRITE (6,49) II
    3 V(I,1) = VT
      CEN(I) = VT
      IF (IP.EQ.1) GO TO 4
      BL(I) = BL(I)+AMAX1(EP,EP*ABS(BL(I)))
      BU(I) = BU(I)-AMAX1(EP,EP*ABS(BU(I)))
    4 SUM(I) = VT
C
C
      NCE = 1
C            NUMBER OF CONSTRAINT EVALUATIONS
      I = 1
      IF (KE(V(1,1)).EQ.0) GO TO 5
      IF (NPR.LE.0) GO TO 12
      WRITE (6,50)
      GO TO 12
    5 NFE = 1
C
C   NUMBER OF VERTICES (K) = 2 TIMES NO. OF VARIABLES.
      K = 2*NV
C
C   NUMBER OF DISPLACEMENTS ALLOWED.
```

```
      NLIM = 5*NV+10
C
C     NUMBER OF CONSECUTIVE TRIALS WITH UNCHANGED FE TO
C     terminate.
      NCT = NLIM+NV
      ALPHA = 1.3
      FK = K
      FKM = FK-1.
      BETA = ALPHA+1.
C
C     INSURE SEED OF RANDOM NUMBER GENERATOR IS ODD.
      IQR = R*1.E7
      IF (MOD(IQR,2).EQ.0) IQR=IQR+101
C
C                             SET UP INITIAL VERTICES
      FUN(1) = FE(V(1,1))
      YMN = FUN(1)
    6 FI = 1.
      FUNOLD = FUN(1)
C
      DO 15 I=2,K
      FI = FI+1.
      LIMT = 0
    7 LIMT = LIMT+1
C
C     END CALCULATION IF FEASIBLE CENTROID CANNOT BE FOUND.
      IF (LIMT.GE.NLIM) GO TO 11
C
      DO 8 J=1,NV
C
C     RANDOM NUMBER GENERATOR  (RANDU)
      IQR = IQR*65539
      IF (IQR.LT.0) IQR = IQR+2147483647+1
      RQX = IQR
      RQX = RQX*.4656613E-9
      V(J,I) = BL(J)+RQX*(BU(J)-BL(J))
      IF (IP.EQ.1) V(J,I)=AINT(V(J,I)+.5)
    8 CONTINUE
C
      DO 10 L=1,NLIM
      NCE = NCE+1
      IF (KE(V(1,I)).EQ.0) GO TO 13
C
      DO 9 J=1,NV
      VT = .5*(V(J,I)+CEN(J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(J,I) = VT
    9 CONTINUE
C
   10 CONTINUE
C
   11 IF (NPR.LE.0) GO TO 12
      WRITE (6,51) I
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,I,FUN,CEN,I)
   12 IER = -1
      GO TO 48
C
   13 DO 14 J=1,NV
      SUM(J) = SUM(J)+V(J,I)
   14 CEN(J) = SUM(J)/FI
C
C     TRY TO ASSURE FEASIBLE CENTROID FOR STARTING.
      NCE = NCE+1
      IF (KE(CEN).EQ.0) GO TO 60
      SUM(J) = SUM(J) -V(J,I)
      GO TO 7
   60 NFE = NFE+1
      FUN(I) = FE(V(1,I))
   15 CONTINUE
```

```
C
C    END OF LOOP SETTING OF INITIAL COMPLEX.
       IF (NPR.LE.0) GO TO 17
       CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
C
C    FIND THE WORST VERTEX, THE 'J'TH.
       J = 1
C
       DO 16 I=2,K
       IF (FUN(J).GE.FUN(I)) GO TO 16
       J = I
    16 CONTINUE
C
C    BASIC LOOP.  ELIMINATE EACH WORST VERTEX IN TURN.
C    it must become NO LONGER WORST, NOT MERELY IMPROVED.
C    find next-to-vertex, THE 'JN'TH ONE.
    17 JN = 1
       IF (J.EQ.1) JN = 2
C
       DO 18 I=1,K
       IF (I.EQ.J) GO TO 18
       IF (FUN(JN).GE.FUN(I)) GO TO 18
       JN = I
    18 CONTINUE
C
C    LIMT = NUMBER OF MOVES DURING THIS TRIAL TOWARD THE
C     centroid DUE TO FUNCTION VALUE.
       LIMT = 1
C
C    COMPUTE CENTROID AND OVER REFLECT WORST VERTEX.
C
       DO 19 I=1,NV
       VT = V(I,J)
       SUM(I) = SUM(I)-VT
       CEN(I) = SUM(I)/FKM
       VT = BETA*CEN(I)-ALPHA*VT
       IF (IP.EQ.1) VT = AINT(VT+.5)
C
C    INSURE THE EXPLICIT CONSTRAINTS ARE OBSERVED.
    19 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
       NT = NT+1
C
C    CHECK FOR IMPLICIT CONSTRAINT VIOLATION.
C
    20 DO 25 N=1,NLIM
       NCE = NCE+1
       IF (KE(V(1,J)).EQ.0) GO TO 26
C
C    EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING VERTEX
C    through the BEST VERTEX.
       IF (MOD(N,KV).NE.0) GO TO 22
       CALL FBV (K,FUN,M)
C
       DO 21 I=1,NV
       VT = BETA*V(I,M)-ALPHA*V(I,J)
       IF (IP.EQ.1) VT = AINT(VT+.5)
    21 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
       GO TO 24
C
C    CONSTRAINT VIOLATION:  MOVE NEW POINT TOWARD CENTROID.
C
    22 DO 23 I=1,NV
       VT = .5*(CEN(I)+V(I,J))
       IF (IP.EQ.1) VT = AINT(VT+.5)
       V(I,J) = VT
    23 CONTINUE
C
```

```
   24 NT = NT+1
   25 CCNTINUE
C
      IER = 1
C
C    CANNOT GET FEASIBLE VERTEX BY MOVING TOWARD CENTROID,
C    OR BY OVER-REFLECTING THRU THE BEST VERTEX.
      IF (NPR.LE.0) GO TO 42
      WRITE (6,52) NT,J
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
      GC TO 42
C
C    FEASIBLE VERTEX FOUND, EVALUATE THE OBJECTIVE FUNCTICN.
   26 NFE = NFE+1
      FUNTRY = FE(V(1,J))
C
C    TEST TO SEE IF FUNCTION VALUE HAS NOT CHANGED.
      AFO = ABS(FUNTRY-FUNOLD)
      AMX = AMAX1(AES(EP*FUNOLD),EP)
C
C    ACTIVATE THE FOLLOWING TWO STATEMENTS FOR DIAGNCSTIC
C    purposes only.
C     WRITE (6,99) J,AFO,AMX,FUNTRY,FUNOLD,FUN(J),FUN(JN)
C    1,NTFS,N
C  99 FORMAT (1X,I3,6E15.7,2I5)
      IF (AFO.GT.AMX) GO TO 27
      NTFS = NTFS+1
      IF (NTFS.LT.NCT) GO TC 28
      IER = 0
      IF (NPR.LE.0) GO TO 42
      WRITE (6,53) K
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
      GO TO 42
   27 NTFS = 0
C
C    IS THE NEW VERTEX NO LCNGER WORST?
   28 IF (FUNTRY.LT.FUN(JN)) GO TO 34
C
C    TRIAL VERTEX IS STILL WORST; ADJUST TOWARD CENTROID.
C    EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING VERTEX
C    through the BEST VERTEX.
      LIMT = LIMT+1
      IF (MOD(LIMT,KV).NE.0) GO TO 30
      CALL FBV (K,FUN,M)
C
      DC 29 I=1,NV
      VT = BETA*V(I,M)-ALPHA*V(I,J)
      IF (IP.EQ.1) VT = AINT(VT+.5)
   29 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
      GC TO 32
C
   30 DO 31 I=1,NV
      VT = .5*(CEN(I)+V(I,J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(I,J) = VT
   31 CCNTINUE
C
   32 IF (LIMT.LT.NLIM) GO TO 33
C
C    CANNOT MAKE THE 'J'TH VERTEX NO LONGER WORST BY
C    displacing toward
C THE CENTROID OR BY OVER-REFLECTING THRU THE BEST VERTEX.
      IER = 2
      IF (NPR .LE. 0) GO TO 42
      WRITE (6,52) NT, J
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
      GC TO 42
   33 NT = NT+1
```

```
      GO TO 20
C
C     SUCCESS:  WE HAVE A REPLACEMENT FOR VERTEX J.
   34 FUN(J) = FUNTRY
      FUNOLD = FUNTRY
      NPT = NPT+1
C
C     EVERY 100'TH PERMISSIBLE TRIAL, RECOMPUTE CENTROID
C     summation to AVOID CREEPING ERROR.
      IF (MOD(NPT,100).NE.0) GO TO 37
C
      DO 36 I=1,NV
      SUM(I) = 0.
C
      DO 35 N=1,K
   35 SUM(I) = SUM(I)+V(I,N)
C
      CEN(I) = SUM(I)/FK
   36 CONTINUE
C
      LC = 0
      GO TO 39
C
   37 DO 38 I=1,NV
   38 SUM(I) = SUM(I)+V(I,J)
C
      LC = J
C
   39 IF (NPR.LE.0) GO TO 40
      IF (MOD(NPT,NPR).NE.0) GO TO 40
C
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,IC)
C
C     HAS THE MAX. NUMBER OF TRIALS BEEN REACHED WITHOUT
C     convergence? IF NOT, GO TO NEW TRIAL.
   40 IF (NT.GE.NTA) GO TO 41
C
C     NEXT-TO-WORST VERTEX NOW BECOMES WORST.
      J = JN
      GO TO 17
   41 IER = 3
      IF (NPR.GT.0) WRITE (6,54)
C
C     COLLECTOR POINT FOR ALL ENDINGS.
C     1)  CANNOT DEVELOP FEASIBLE VERTEX.             IER = 1
C     2)  CANNOT DEVELOP A NO-LONGER-WORST VERTEX.    IER = 2
C     3)  FUNCTION VALUE UNCHANGED FOR K TRIALS.      IER = 0
C     4)  LIMIT ON TRIALS REACHED.                    IER = 3
C     5)  CANNOT FIND FEASIBLE VERTEX AT START.       IER = -1
   42 CONTINUE
C
C     FIND BEST VERTEX.
      CALL FBV (K,FUN,M)
      IF (IER.GE.3) GO TO 44
C
C     RESTART IF THIS SOLUTION IS SIGNIFICANTLY BETTER THAN
C     the previous, OR IF THIS IS THE FIRST TRY.
      IF (NPR.LE.0) GO TO 43
      WRITE (6,55) (M,YMN,FUN(M))
   43 IF (FUN(M).GE.YMN) GO TO 47
      IF (ABS(FUN(M)-YMN).LE.AMAX1(EP,EP*YMN)) GO TO 47
C
C     GIVE IT ANOTHER TRY UNLESS LIMIT ON TRIALS REACHED.
   44 YMN = FUN(M)
      FUN(1) = FUN(M)
C
      DO 45 I=1,NV
      CEN(I) = V(I,M)
      SUM(I) = V(I,M)
```

```
   45 V(I,1) = V(I,M)
C
      DC 46 I=1,NVT
   46 XS(I) = V(I,M)
C
      IF (IER.LT.3) GO TO 6
   47 IF (NPR.LE.0) GO TO 48
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,V(1,M),-1)
      WRITE (6,56) FUN(M)
   48 RETURN
C
   49 FORMAT (50HOINDEX AND DIRECTION OF OUTLYING
     1variable at starti5)
   50 FORMAT (50HOIMPLICIT CONSTRAINT VIOLATED AT
     1start. dead end.)
   51 FCRMAT ('OCANNCT FIND FEASIBLE',I4,'TH VERTEX OR
     1centroid at start.')
   52 FCRMAT (10HOAT TRIAL I4,54H CANNOT FIND FEASIBLE
     1vertex which is no
     2LCNGER WORST,I4,15X,'RESTART FROM BEST VERTEX.')
   53 FORMAT (40HOFUNCTION HAS BEEN ALMOST UNCHANGEC
     1for i5,7h trails)
   54 FCRMAT (27HOLIMIT ON TRIALS EXCEEDED. )
   55 FORMAT('OBEST VERTEX IS NO.',I3,'OLD MIN WAS',E15.7,
     1 '   NEW MIN IS ',E15.7)
   56 FORMAT ('OMIN CBJECTIVE FUNCTION IS ',E15.7)
      END
      SUBROUTINE FBV (K,FUN,M)
      DIMENSION FUN(50)
      M = 1
C
      DO 1 I=2,K
      IF (FUN(M).LE.FUN(I)) GO TO 1
      M = I
    1 CCNTINUE
C
      RETURN
      END
      SUBROUTINE BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FN,C,IK)
      DIMENSION V(50,50), FN(50), C(25)
      WRITE (6,4) NT,NPT,NFE,NCE
C
      DC 1 I=1,K
      WRITE (6,5) FN(I),(V(J,I),J=1,NV)
      IF (NVT.LE.NV) GO TO 1
      NVP = NV+1
      WRITE (6,6) (V(J,I),J=NVE,NVT)
    1 CONTINUE
C
      IF (IK.NE.0) GC TO 2
C
      WRITE (6,7) (C(I),I=1,NV)
      RETURN
    2 IF (IK.GE.0) GC TO 3
      WRITE (6,8) (C(I),I=1,NV)
      RETURN
    3 WRITE (6,9) IK,(C(I),I=1,NV)
      RETURN
C
    4 FCRMAT ('ONO. TOTAL TRIALS = ',I5,4X,
     1'no. feasible trails = ',i5,4x,
     2'NO. FUNCTION EVALUATIONS = ',I5,4X,
     3'nc. constraint evaluations = ',i5/
     4'0      FUNCTICN VALUE',6X,'INDEPENDENT VARIABLES/
     5dependENT OR IMPLICIT CONSTRAINTS')
    5 FCRMAT (1H ,E18.7,2X,7E14.7/(21X,7E14.7))
    6 FORMAT (21X,7E14.7)
    7 FCRMAT (10HOCENTROID 11X,7E14.7/(21X,7E14.7))
    8 FCRMAT ('0  BEST VERTEX',7X,7E14.7/(21X,7E14.7))
```

```
    9 FORMAT ('OCENTROID LESS VX',I2,2X,7E14.7/(21X,
     17e14.7))
      END
      FUNCTION FE(X)
      DIMENSION X(3)
      COMMON TDIFF
      CALL PLANT(X)
      FE=TDIFF
      RETURN
      END
      FUNCTION KE(X)
      DIMENSION X(3)
      KE=0
      RETURN
      END
//GO.SYSIN DD *
/*
//GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A341
```

APPENDIX B

EXAMPLE PROBLEM USING ICSOS

The purpose of this example is to demonstrate the performance of the program. Consider the control system of Figure 4.1 with controller C. Figure B.1 shows the block diagram to evaluate the controller parameters.

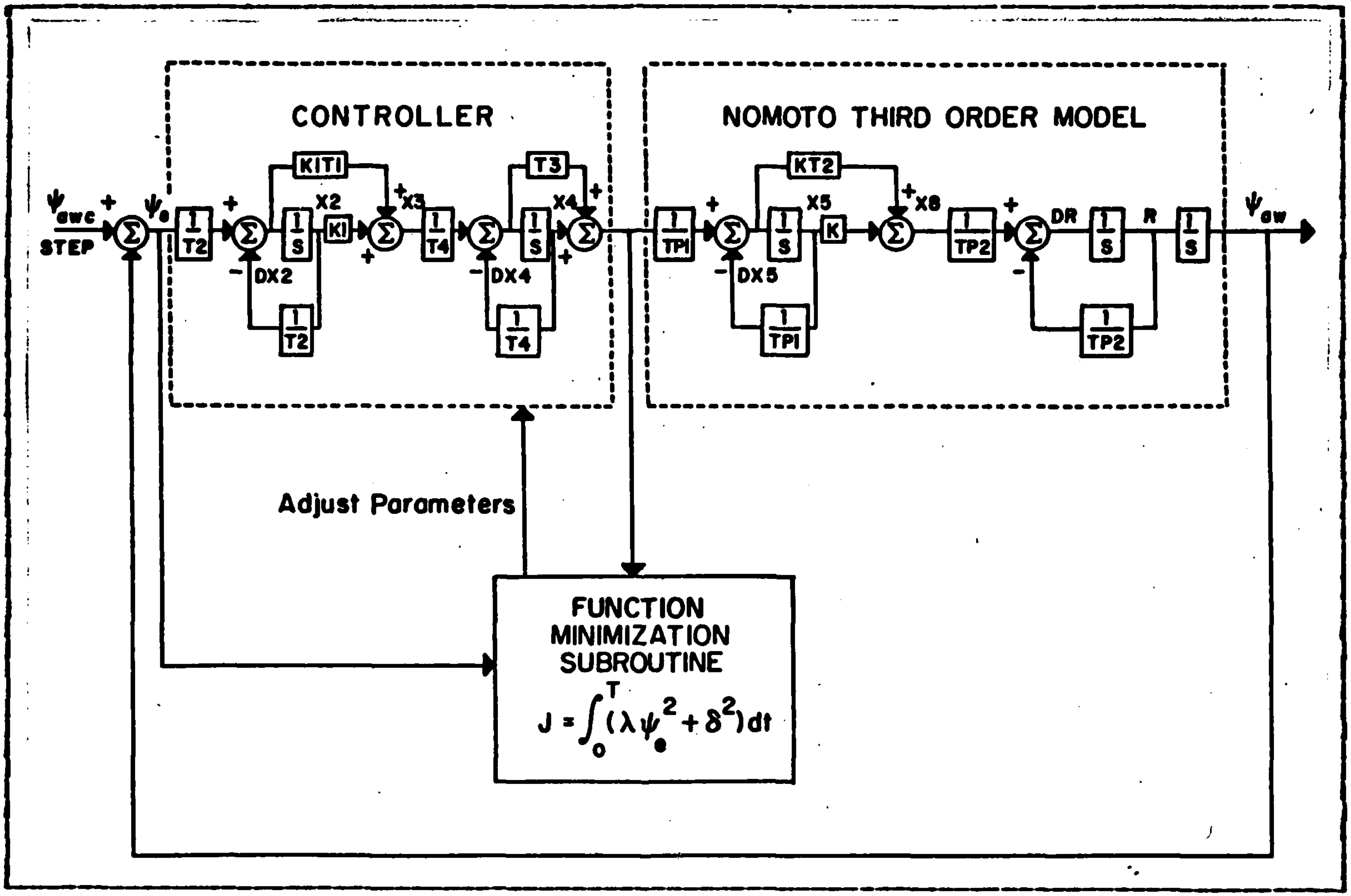

Figure B.1 DETAIL BLOCK DIAGRAM

The differential equations describing the system and its desired performance are:

$\dot{X}2$=DX2

$\dot{X}4$=DX4

$\dot{X}5$=DX5

$\dot{R}$ =DR

$\dot{YAW}$=R

Defining the following cost function:

$$J=\int(LAMDA*YAWE**2+D**2)\,dt$$

Defining the special functions:

```
YAWE=YAWC-YAW
DX2=(YAWE-X2)/T2
X3=K1*(T1*DX2+X2)
DX4=(X3-X4)/T4
d=(t3*dx4+x4)
dx5=(d-x5)/tp1
x8=k*(tz*dx5+x5)
dr=(x8-r)/tp2
```

Defining the constants:

```
YAWC=1.0
K=.14771
TZ=11.2833
TP1=6.4699
TP2=53.7931
LAMDA=4.2
```

and using YAWC=1.0 the optimal solution found by the program is:

```
K1=.4179916
T1=53.69932
T2=4.970023
T3=6.294369
T4=13.85919
COST=68.04735
```

Table 34 shows the specifications of this problem with the free parameter optimum values found. Figure B.2 shows the actual yaw and rudder response.

TABLE 34

ICSOS OUTPUT

```
-----SPECIFICATIONS-----

VARIABLES & INITIAL CONDITIONS:
X2 = .0
X4 = .0
X5 = .0
R = .0
YAW = .0
J = .0
TIME = .0

CONSTANTS:
YAWC = 1.000000000
K = .1477100000
TZ = 11.2833000
TP1 = 6.4699000000
TP2 = 53.79310000
LAMDA = 4.20000000

FREE PARAMETERS:
K1 : OV= .4179916 LL= .1000000 UL= 1.000000
T1 : OV= 53.69928 LL= 1.000000 UL= 100.0000
T2 : OV= 4.970029 LL= 1.000000 UL= 10.00000
T3 : OV= 6.294369 LL= 1.000000 UL= 10.00000
T4 : OV= 13.85917 LL= 1.000000 UL= 20.00000

SPECIAL FUNCTIONS:
YAWE = YAWC-YAW
DX2 = (YAWE-X2)/T2
X3 = K1*(T1*DX2+X2)
DX4 = (X3-X4)/T4
D = (T3*DX4+X4)
DX5 = (D-X5)/TP1
X8 = K*(TZ*DX5+X5)
DR = (X8-R)/TP2

DERIVATIVES:
D(X2 /D(TIME ) = =
      DX2
D(X4 /D(TIME ) = =
      DX4
D(X5 /D(TIME ) = =
      DX5
D(R /D(TIME ) = =
      DR
D(YAW /D(TIME ) = =
      R
D(J /D(TIME ) = =
      LAMDA*YAWE**2+D**2

OUTPUTS:
   TITLE: ACTUAL YAW AND RUDDER RESPONSE
   TABULATE: TIME     D        R        YAW
      AT INTERVAL     2.000000000
   PLOT: D        YAW
      AGAINST: TIME    AT INTERVAL    2.000000000

END CALCULATION WHEN TIME .GE. 600.000
```

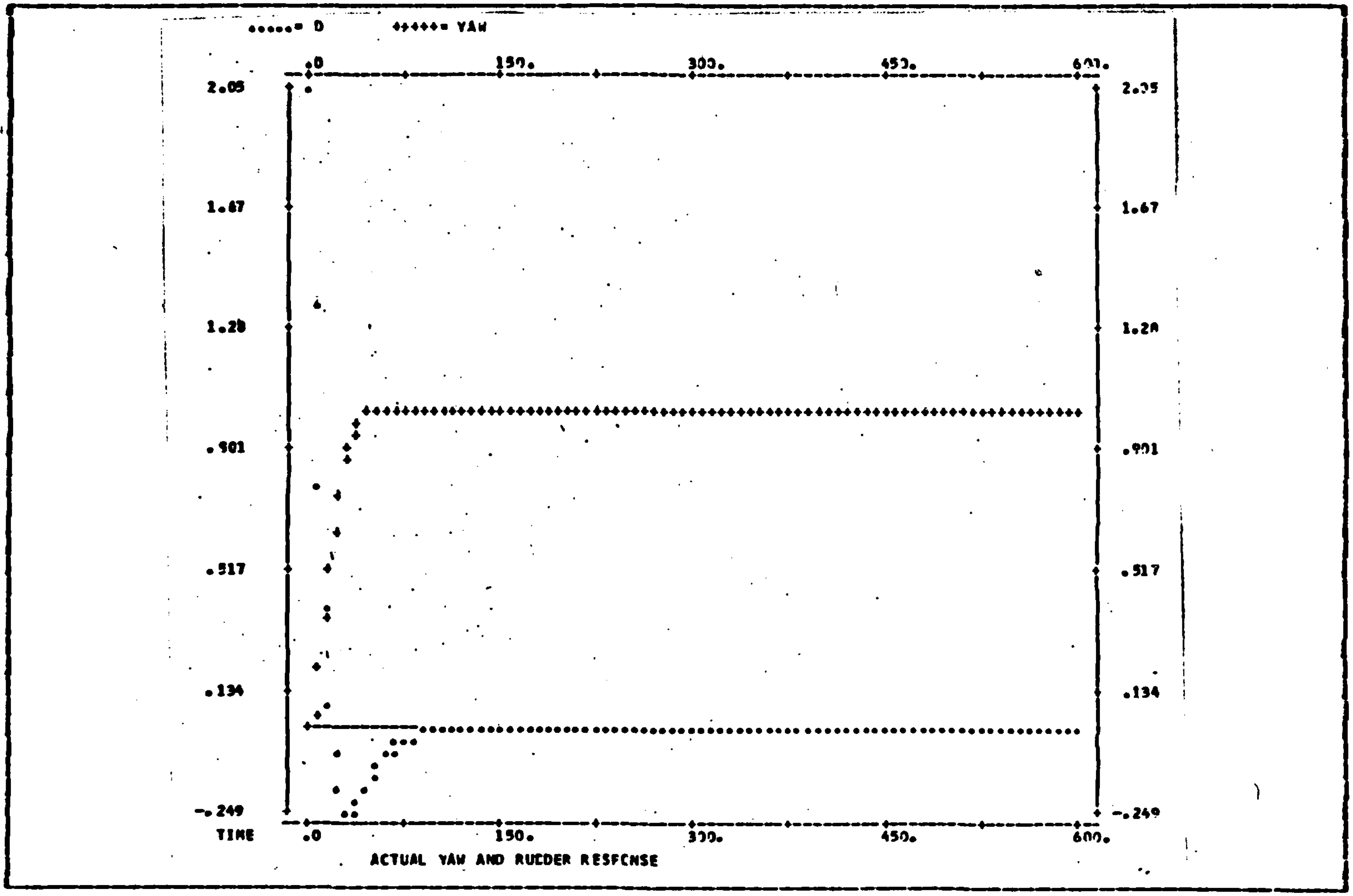

Figure B.2 YAW AND RUDDER vs. TIME

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